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Review

Comprehensive educational framework on the application of 3D technologies for the restoration of cultural heritage objects

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ABSTRACT

Over the past decade, the use of 3D scanning, virtual reconstruction and digital manufacturing in the preservation of cultural heritage (CH) has gained significant attention, among other for the restorative intervention of loss compensation. These techniques have been explored both in conservation-restoration (CR) practices and research facilities. However, despite this progress, there is a notable absence of an educational framework specifically designed for virtual restoration methods aimed at physical restoration. As a result, CR practitioners motivated to execute a virtual restoration are either challenged to find their way in a wealth of information or have to rely on 3D experts for guidance and digital tasks.

This article discusses this gap by detailing the construction and validation of an educational framework for loss compensation on CH objects. Drawing upon an extensive review of past case studies, an “Overview of possibilities on the application of 3D technologies for restoration of CH objects” (shortened to Overview OP) is compiled of involved reasons, processes, methods and materials to consider within a virtual restoration workflow. The composed Overview consists of eight phases, distinguishing 22 steps, encompassing both traditional restorations steps, virtual steps and combined steps in which material, object, device and product-related possibilities are displayed.

To assess its effectiveness, an experimental set-up was devised, incorporating a pre and post-test, short-term and long-term usability testing, and an evaluation questionnaire. This set-up was implemented within an educational context involving third-year bachelor students in CR at the University of Antwerp ($n = 17$).

Although the Overview OP does require a learning curve and may initially appear overwhelming, the experimental results demonstrated it organisational structure. It was found to be highly useful, time-saving and capable of efficiently guiding CR practitioners towards relevant information tailored to their specific cases.

Following the validation process, the Overview OP was improved based on the received feedback. Additionally, a literature update was conducted, expanding the Overview OP to include cases executed between 2020 and 2023. The finalised version, along with the accompanying “Inventory of cases” is now accessible open-source on an online platform.

1. Introduction and research aim

The increasing prevalence of 3D digital technologies in cultural heritage (CH) applications, particularly in the conservation and restoration (CR) practice, has underscored the need for comprehensive and educational frameworks. The London Charter and consequent Seville Principles already proved valuable documents to create a shared understanding of computer-based visualisations. While the London charter established ground rules for visualisation of the entire concept of CH, it laid a robust foundation for the Seville Principles, which focuses on Virtual Archaeology [1,2]. In addition, valuable initiatives to discover, learn and perform 3D scanning methodologies have been constituted over the years since digitisation found its application in CH documentation. These ini-

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tiatives are often the outcome of individual research projects in which (choosing) a digitisation strategy takes a key role [3–6] or as outcomes of European international studies, resulting in guidelines and the addition of 3D models to digital CH databases (e.g. Europeana [7]). This includes the CARARE project [8], the follow-up project 3D-ICONS [9] and accompanying extensive study reports for CH professionals to consult, including important parameters, formats, standards, benchmarks, methodologies and guidelines for digitisation strategies [10].

However, these mentioned guidelines primarily focus on data acquisition and the production of a 3D model for engaging in research, preservation, dissemination, education and tourism-related objectives, as a 3D model is considered the end product of the digital workflow.

Although 3D models can serve as supporting media for CR or for research purposes [11], they are increasingly invaluable as tools for restoration methodologies. In this context, the 3D model functions not just as an end-product but also as an auxiliary or intermediary tool aiding the physical restoration workflow. With the aim of a physical restoration, the 3D model can as such facilitate customised structural supports or compensate losses in CH objects.

Despite research projects and publications detailing physically restored cases, there is a notable absence of initiatives guiding CR practitioners and students through the various steps of using 3D technologies in restoration methodologies, and inter alia, to the sources of data acquisition mentioned before. Moreover, some of the main concerns CR practitioners face when (thinking of) implementing 3D technologies in their work include the suitability of the 3D printing process and its materials, next to the required knowledge to effectively and qualitatively apply these technologies [12]. Therefore, when a virtual restoration workflow is deemed advantageous for the restoration of a CH object, emerging or professional CR practitioners have to search for a suitable methodology without a comprehensive understanding of the challenges and opportunities involved.

Collaboration with 3D experts has been documented in the literature, as will be discussed in this article, underlining the value of shared research and ideation [13]. This is especially applicable to the difference in ethical rationale and decision-making from a CR point of view compared to the technical point of view found in 3D experts. Therefore, it is highly beneficial for CR practitioners to acquire basic knowledge when engaging in virtual restoration workflows, even when outsourcing digital tasks to 3D experts.

Another challenge is found in the dissemination of scientific research output. Documented cases executed by research facilities and presented in academic literature, may struggle to reach their intended audience due to unfocused dissemination, paywalls, complex jargon or complicated research set-ups. Efficient dissemination strategies necessitate clear objectives, open-access publications, visually appealing content, appropriate media selection and active participation encouragement, among other [14].

Also, the practitioner's interest lays generally in practical recommendations and thus an increase in scientific output does not necessarily enhance the availability and manageability of the research results [13]. To tackle the need for more education and more applied experience it is therefore necessary that the translation is made in comprehensive but comprehensible frameworks directed towards its targeted audience in a clear, understandable and open-access manner. As far as the authors are aware an educational framework (such as a handbook or guide) on the use of 3D technologies within the CR practice does not yet exist, nor is it constructively being taught in art conservation programs.

An educational framework can also be termed a process worksheet in the educational literature (e.g. [15]) and such process worksheets have the advantage of both learning *from* and learning *with*. These are tools that facilitate meaningful professional thinking and working and they help approach a problem at hand as the best-informed expert in a domain would [16,17]. Therefore, process worksheets can be educational devices both for the novice learner and the seasoned practician willing to improve their skillset.

The first research question and goal comprised the challenge on how to make such a process worksheet, to guide restorers in their knowledge gathering when faced with a case study which could benefit from applying 3D technologies. An *Overview of possibilities on the application of 3D technologies for restoration of CH objects* (hereafter referred to as the Overview OP) was made based on qualitative data analysis of case studies found in a literature review (up to and until 2020) in which the methodologies are categorised to form a virtual restoration workflow (Section 2).

The second research question regarding the constructed Overview OP was to know if it is an effective tool to gain insights on 3D technologies and to guide the user towards answers concerning the application of 3D technologies for the restorative intervention of loss compensation on a CH object. This question consists of three parts, for which an experiment was designed. Firstly, to know if the participants gained knowledge of 3D technologies, a pre and post-test were set up, to be taken before and after the experiment (Section 3.1). Secondly, to know if it is an effective tool, user experience was collected during a Thinking Aloud Method (TAM) protocol (Section 3.2). Thirdly, to know if it can help the users to get answers for a case, the participants were asked to write a treatment proposal (Section 3.4). Finally, to evaluate this process and to get feedback on (the use of) the Overview OP, the experiment was concluded by an evaluation questionnaire (Section 3.4). Based on these results and the received suggestions (Section 4) the Overview OP was revised and improved, including an update on the literature for the period of 2020–2023 (Section 5).

2. Construction of the Overview of possibilities

2.1. Literature review

In 2020, a systemic literature review was executed as part of a study to find all the restoration projects in which 3D technologies assisted in loss compensation. This provided 56 documents, presenting 65 case studies. The full description of the literature review is described in Acke et al.[12].

The databases searched were:

- Scientific peer-review databases: Web of Science, Scopus, ACM Digital Library, IEEE Xplore, ScienceDirect, ISPR Archives
- Scientific non-peer-reviewed databases: Google Scholar, ResearchGate, Academia
- Art and restoration-related databases: Jstor, CoOl, AATA, ICOM-CC, CeROArt
- Non-academic field, to include the professional CR practice: Google

The initial keyword search was *3D digital restoration cultural heritage* and this was expanded with the following word combinations after analysis of the found publication's keywords:

- *3D, technology*
- *Virtual, digital*
- *Computer-aided, model, modelling*
- *Printing, additive manufacturing, rapid prototyping, digital fabrication*
- *Art, restoration, conservation, cultural heritage*

Of the found publications, a back and forward search was executed through Google Scholar.

The found cases were selected based on the goal of loss compensation. These cases were used to construct the Overview OP

(Section 2.2). After the validation of the Overview OP, a literature update was performed to find cases published between 2020 and 2023. The same databases and keywords were used.

2.2. Qualitative data analysis of the cases and construction of the Overview OP

The 65 case studies were read and analysed in the qualitative data analysis software Nvivo 12 pro. A virtual restoration workflow [18] is used as a base structure for the content analysis of the cases. Text fragments were put in the relevant step of the workflow e.g. information about the 3D scanning of the case object, which is categorised underneath the step "3D scanning". Each collection of information gathered in the relevant step of the workflow was subsequently categorised into modules in which each relevant and documented possibility is presented e.g. In the step 3D scanning, there is a module "Method of 3D scanning" and this was subdivided into "Structured Light Scanning", "Laser Scanning, "Photogrammetry",... As such, a structure of all the documented possible options emerged. Subsequently, this information was put into a comprehensive table in Microsoft Word to form the Overview of possibilities, including phases, steps, modules and eventually the various possibilities. Hereafter these parts are also mentioned with a capital letter, to distinguish the parts in the Overview OP from the general use of the words e.g. Phases, Steps, Modules, and Possibilities. The references were added beneath each Possibility (through reference manager Mendeley), which has mentioned or documented the said Possibility. This provides a benchmark of the more represented options, while also providing a hyperlink towards the reference source.

As the novelty of these cases is focused on the application of 3D technologies, it was noticed traditional restoration steps were less discussed, both quantitatively and qualitatively. This can be related to the focus on loss compensation and the fact that many of the study objects did not have prior restorations or other types of damages which needed treatment.

The Overview OP is preceded by an introductory text, to explain its purpose and how to use it, and a Summary table of the Steps, along with exemplary questions to be asked during the workflow.

A tool to help restorers find similar case studies is made available through the *Inventory of cases* (hereafter referred to as the Inventory OC). Two versions are presented: First, a short version is presented in the Overview OP itself, which includes the reference number, authors, material type, object specification and an indication of the missing part. Secondly, a full version, in a separate Excel file, contains descriptive data of the references and allows for filtering on authors, year, type of publication, background of the authors, material type and specification, object type and specification and missing part. This full version can be updated more easily (compared to the Overview OP) when new cases are executed and will allow for a recent view on advances in loss compensation with 3D technologies.

The Overview OP is meant to be used as a digital document, because of the navigating functions, pop-up info and hyperlinks. But it is organised on an A3 paper size, to be able to print it and use it as a reference document.

Finally, It must be emphasized the Overview OP is a snapshot of the performed case studies up until this publication. Undoubtedly, many more cases have already been executed by private practitioners, but are not publicly documented and are as such not found and incorporated in the Overview OP. Moreover, only information

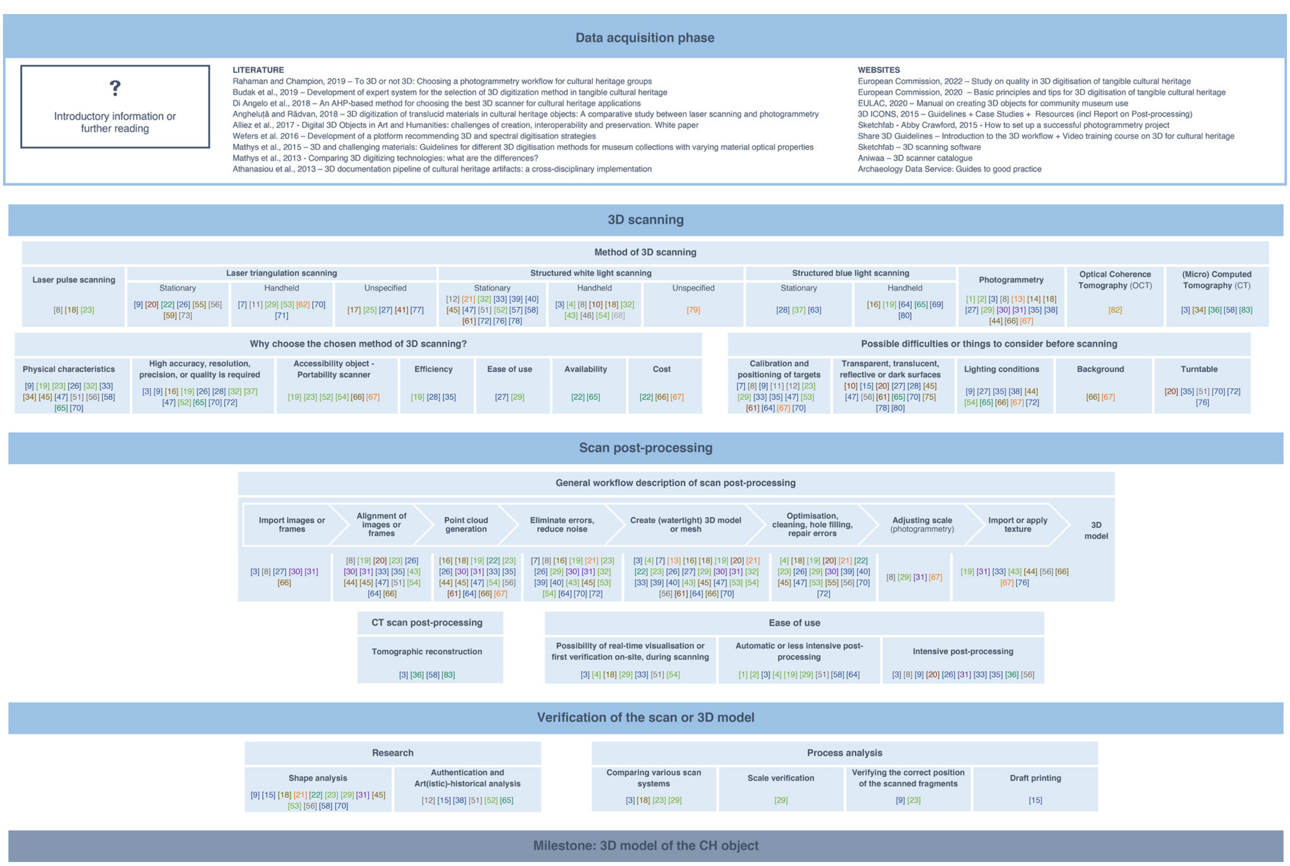

Fig. 1. Example of the Phase Data acquisition, including three Steps; 3D scanning, Scan post-processing and Verification of the scan or 3D model, concluding with the Milestone of an acquired 3D model.

Table 1
Distribution of material specialities of the participants in the control and experimental group.

	Exp. group	Control group
Ceramics	1	3
Metal	–	2
Paintings	6	1
Paper	–	2
Visual Media	–	2
Stone(/Murals)	4	1
Wood(/polychromy)	–	4
Glass	2	–
Textiles	4	–
Total	17	15

found in the case studies is processed. This means that for every Step other viable options exist or can be explored. Every documented case is considered equal in the Overview OP, but it is up to the reader to critically reflect on the given information in the publication. Additionally, the information which is categorised in Phases, Steps, Modules and Possibilities is an individual interpretation of the first author, manually coded into a logical sequence. Therefore it might contain errors, incompleteness or misinterpretations. Users of the Overview OP and authors of included cases are encouraged to contact the first author if feedback is in place. In Fig. 1, an example is given of one of the Phases. The full Overview OP (Appendix A) and Inventory OC (Appendix B) can be found online in the supplementary material and can be accessed via Mural.

3. Educational validation of the Overview of possibilities

A small-scale experiment was designed to provide support for the content and construct validity of the Overview OP as an educational tool. The design was aimed to quantify the knowledge of the participants before and after the experiment and to correlate this with the use of the Overview OP.

The assignment of participants was only partly at random. The experiment was situated within a practical restoration course of the third bachelor (3BA) students of the conservation-restoration program of the University of Antwerp. This practical course, Implementation IIIB (of the academic year 2020–2021), focuses on the learning of restoration treatments and its organisation is subdivided into material labs. It was the lecturer of the lab who decided if it would fit in their semester program and as such selected the experimental group of this study ($n = 17$). The remaining 3BA ($n = 15$) students participated as a control group. The experimental group included two students for whom participation was beneficial for their master thesis dissertation. The distribution of specialities and amount of participants is given in Table 1.

The experiment consists of four parts, which will be explained in the following sections. Both the control and experimental groups performed the pre and post-test, the experimental group further participated in the usability testing with TAM exercises, wrote a treatment proposal and completed the evaluation questionnaire.

3.1. Pre and post-test

A factorial pre-post design enabled to quantify the knowledge of the control and the experimental group on the use of 3D technologies. Before and after the usability testing (Section 3.2) and the writing of a treatment proposal (Section 3.3), the participants were asked to complete a test, made in Qualtrics, with statements about 3D scanning, 3D modelling and 3D printing for which the participants had to indicate if the statement was true or false. Out of the 38 statements the participants were randomly assigned 15 statements. For a correct answer, they gained 1 point, for a wrong answer 0,5 point was subtracted. To prevent guessing, they could indicate they do not know the answer, leading to 0 points. A *t*-test of the pre-test using bootstrapped data indicates that there is no significant difference between the experimental and control group, with $t(28.68) = 0.74$, $p = 0.356$, (CI: −0.78, 2.25), which supports the notion that randomisation was successful. The list of statements can be found in Appendix C.

This part was rated by comparing the pre-test with the post-test scores of both the experimental and control groups. The participants were also asked to what extent they felt confident during answering the questions, to what extent they guessed and to what extent they indicated “I don’t know” because it was the easiest answer. Lastly, it was surveyed to what extent they felt motivated to execute a restoration project with 3D technologies and how confident they felt to execute such a project.

3.2. Usability testing

Usability testing using the Thinking Aloud Method (TAM e.g. [19]) whereby participants think aloud during the solution process allows for the surveyor to receive immediate feedback from the participant. As such, the Overview OP could be qualitatively evaluated on usability, specifically on how clear and practical it is to consult. This part was performed during an online meeting (+-1 h) with each participant individually.

The main part of the usability testing consisted of ten scenario questions, each focusing on a part of the Overview OP, necessary to effectively understand and use the Overview OP. These scenario questions were preceded with an exemplary exercise for the participant to get accustomed to the TAM (Googling and solving a rebus puzzle). Questions 4 to 8 were questions about a case study, a skull needing reconstruction (taken from [20]). A script with the questions was made to ensure all participants were subjected to the same procedure (Appendix D). A score of 0 to 3 was given depending on how successful the task was completed. When the participant succeeded in the task, within a reasonable time, used the foreseen method and gave the right answer, 3 points were given. When the participant understood the task but had to search and try different ways to complete the task, or if the participant partly succeeded in completing the task, by completing it in another way or by giving another answer, 2 points were given. When the participant understood the task but had to search and try multiple ways to complete the task, taking a long time, or if the participant understood the task, and was on the right path, but ultimately gave up, only 1 point was given. If the participant gave up or refused to complete the task, 0 points were appointed.

The ten parts to evaluate were:

1. The use of the Summary table as a content table to explore which steps can be undertaken in a virtual restoration workflow.
2. Exploration of the Steps and their hyperlink in the Summary table to go to the relevant step in the Overview OP.
3. Using the cited references as a benchmark (e.g. the more references cited, the more common a possibility is)
4. The ability to search for a case study in the Overview OP can function as a guide for a similar case study a restorer can encounter in its practice.
5. Use Ctrl + F to search a specific case and to look for its undertaken Steps.
6. Use Ctrl + F for browsing and navigating the Overview OP to find relevant information.
7. Critical reflection on the content of the Overview OP (e.g. is the information provided in the sources and given in the

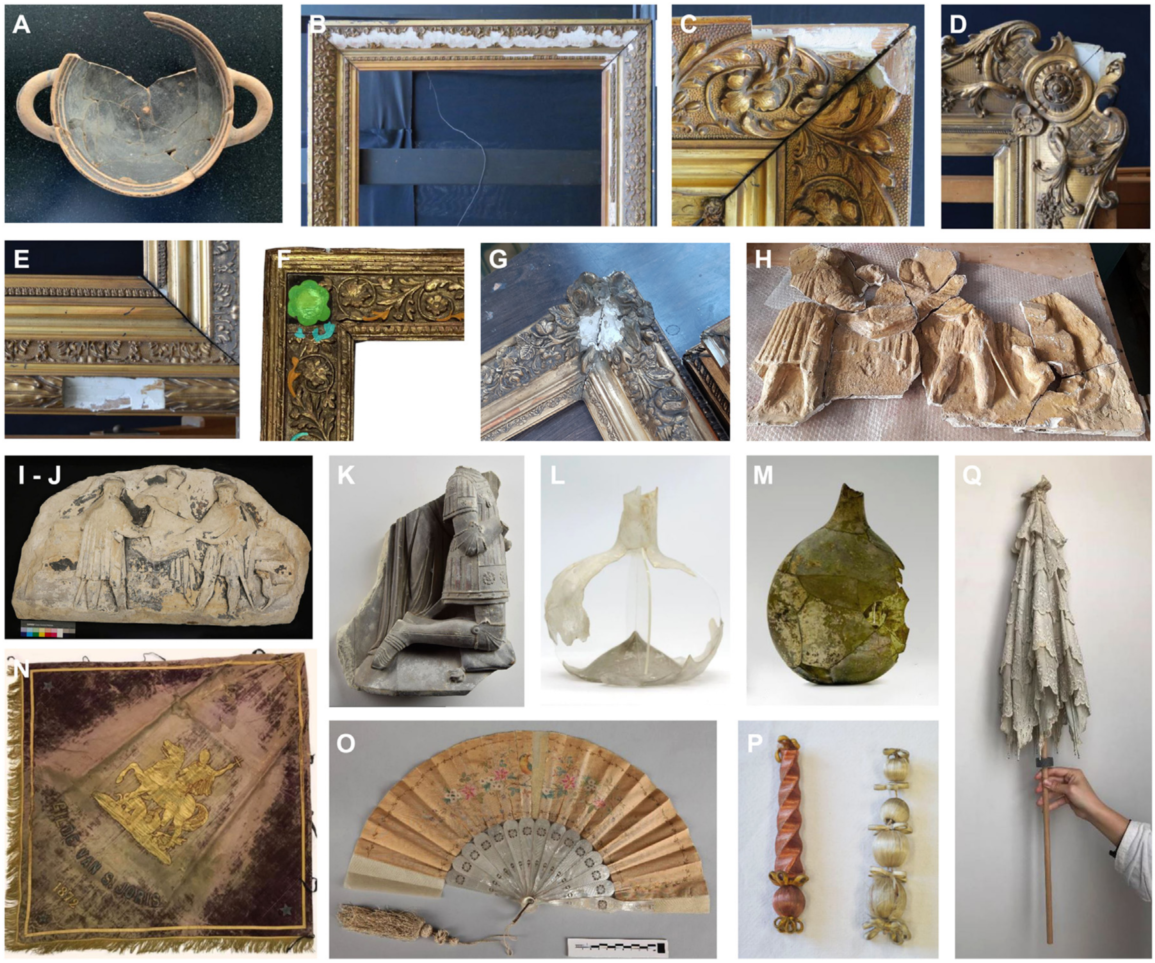

Fig. 2. Selected case study objects, discussed with participant and lecturer. Pictures taken by the participants © A: Private collection Roald Doctor (Ghent University). B-G and L-M: Collection University of Antwerp. H-J: Archaeological depot of Antwerp. K: Museum M, Leuven. O and Q: Private collection Natalia Ortega Saez (University of Antwerp). N: Guild of Sint-Joris, Rijkevorsel. P: Meir Palace, Antwerp.

Overview OP undeniably correct and safe to use in every case?)

8 Use the hyperlink of the references to go to the online source and read the publication.

9. Use the references as a linking tool between the various Steps (e.g. by searching for 3D printing materials, one can deduct which 3D printing technology can process these materials)

10. Interpret a case workflow by searching for the citation of that case in the Modules.

3.3. Treatment proposal

After the introduction of the Overview OP during the TAM scenario exercises, the experimental group was asked to write a treatment proposal for a case study object of their speciality (e.g. ceramics, stone, glass, painting (frame), textiles). The case studies were selected for their potential to use 3D technology and in consultation with the lecturer, to ensure its feasibility. The participants had a time frame of five weeks to write the proposal and next to the Overview OP and cited references which were made available through a shared folder, they were free to consult every source available. It was emphasized that the proposal should be realistic and feasible, meaning the methods should be described in detail and be relevant to the object, choices should be grounded, and possible pitfalls should be noticed and if possible anticipated. The learning competencies, which were used as evaluation criteria, were stated clearly to the participants (Table 2).

The selected case studies (Fig. 2) and the goals of the intervention were:

A. To create a detachable filling for an earthenware skyphos.
B. To complete missing ornaments on the whole side of a painting frame.
C. To complete missing parts on the sides and corners of a painting frame.
D. To complete missing ornaments (voluminous) on a corner of a painting frame.
E. To complete missing ornaments in the middle of a painting frame.
F. To complete a missing rosette on a corner of a painting frame.
G. To complete missing ornaments (small, detailed) on a corner of a painting frame.
H. To make a virtual reconstruction of the moulds of a stone facade bas-relief, to map the damage of the reliefs.
I. To make a virtual reconstruction of the lost polychrome decoration of a stone façade bas-relief.
J. To make a structural support for a stone façade bas-relief.
K. To reconstruct the missing head on a stone epitaph.
L. To reconstruct (the majority of) missing parts of an archaeological bottle.
M. To reconstruct missing parts of an archaeological bottle.

Table 2
Evaluation criteria based on the learning competencies of the 3BA practical restoration course.

Point weight	Learning competencies	How to achieve the learning competency		
20 pts		0 to 3 pts	4 to 6 pts	7 to 10 pts
	The student can write a fitting and realisable treatment proposal	The proposal is not thoroughly/concretely/logically described The proposal is not realistic or feasible. The methodology is not described or not tailored to the study object	The proposal contains basic information but lacks detail or concreteness. Subject to (minor) modification, the proposal is suitable for the study object and is feasible.	The proposal is thoroughly, concretely, and logically described. The proposal is realistic and can be implemented as described. The methodology is relevant and tailored to the study object
15 pts		0 to 1 pts	2 to 3 pts	4 to 5 pts
	The student can analyse a complex case and can critically reflect on sources and literature, relevant to the case	The complexities or difficulties specific to the case study have not been described Potential pitfalls are not described or anticipated The choices made in the proposal are too brief. No different possible options have been cited and/or compared with each other. No suggestions have been given on possible research tracks	Some difficulties were described, but the complexity of the case study was not fully understood (Some) potential pitfalls have been detected, but no anticipation is foreseen Several options are cited, but it is unclear which of the techniques/methods is appropriate. No suggestion has been made as to how this can be figured out	The complexities or difficulties specific to the case study are well-described Potential pitfalls have been detected and realistically anticipated The choices made, described in the proposal, are well-founded. Where a choice has been left undecided, a research track/experiment has been suggested.
5 pts		0 to 1 pts	2 to 3 pts	4 to 5 pts
	The student takes initiative, can work independently, consults with experts, can make interdisciplinary connections	No links have been established between a traditional CR treatment and the use of 3D technology	Limited links have been established between a traditional CR treatment and the use of 3D technology	Relevant or applicable links have been made between a traditional CR treatment and the use of 3D technology

N. To make a virtual reconstruction of the central figure on a guild banner.
O. To complete a missing pearl leg from a textile fan.
P. To reproduce passementerie wooden cores to restore a canopy.
Q. To make a fitting handle for a textile parasol.

Each proposal was evaluated by two lecturers with expertise in the participants' material speciality and two lecturers/researchers with expertise in 3D technologies. The evaluation is based on the learning competencies defined in the ECTS fiche (European Credit Transfer and Accumulation System) of the said practical restoration course (Table 2). A total of 40 points was to be appointed, converted to a score on a max of 10 points.

3.4. Evaluation questionnaire

An evaluation questionnaire was designed to get a sense of the validity of the tool after prolonged and intensive use of the Overview OP while the participants were tasked with writing a treatment proposal (Section 3.3). The questions, aimed at describing their experience during writing their proposal, allowed to quantitatively compare the usage of the various parts of the Overview OP with their first experience during the TAM session.

Ranking or rating questions, in which the suggestions were given, and needed to be marked on a degree of applicability, involved: Which type of sources did you consult (divide 100%)? Are the statements provided applicable to how you used the Overview OP ((Rather) yes – no)? Are the statements provided applicable to how you wrote your proposal ((Rather) yes – no)? Which parts of the Overview OP were meaningful or unnecessary (scale of 0–10)? Could the provided suggestions be an added value for (the use of) the Overview OP ((Rather) yes – no)? Open questions involved: How did you use the Overview OP? Which things did you find difficult or easy? Which answers did you not find? How much time did you spend researching and writing the proposal? What are the strengths and weaknesses of the Overview OP?

Finally, words from the Microsoft Production Reaction Cards [21] were given, asking the participants to mark 10 words which they found fitting with (their experience about) the Overview OP. Out of the standard amount of 110 words, 78 words were selected and given in the questionnaire (see Appendix F).

4. Results and discussion

The majority of both the experimental and control group participants had no previous experience concerning 3D technologies. Two students had limited experience with photogrammetry. Five students had previous experience with 3D printing: mostly during previous education (art/architecture/product development - high school/higher education) or at home. Their experience included FDM printing with ABS and other undefined plastics, the students mentioned the print was often executed for them or they do not recall which technique or material was used. One student had experience with laser cutting. The most experience was found in 3D modelling, 12 students have tried 3D modelling before, mostly during previous (art/architecture/product design) courses, using Sketchup, Solidworks, Meshmixer, Maya, Blender, OpenSCAD or AutoCAD. One student gained experience in 3D modelling during the experiment.

4.1. Pre and post-test

Comparing the scores of the pre and post-test from the control group to the experimental group's scores (Fig. 3), a slightly significant interaction effect was noted, F(3.63)=5.43, $p = 0.023, \eta_p{}^2 = 0.83$, indicating that the intervention had a small effect on the competence gains. Both the small sample size and the small partial eta squared prevent making big conclusions from the

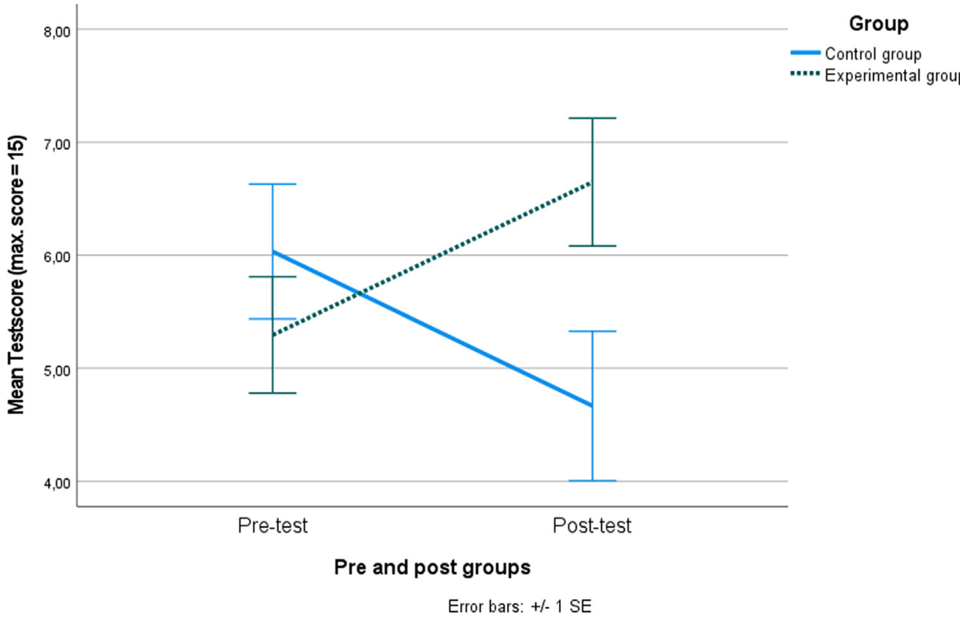

Fig. 3. Results of the pre-test vs. the post-test for both the control and experimental group.

intervention. However, at this point, it provides sufficient support that the Overview OP has potential as a support and learning tool.

Although also in the post-test the experimental group scored below average ($M = 6{,}65$; $SD = 2{,}33$ on a max score of 15), the study (on a Likert scale from 0 (strongly disagree) to 10 (strongly agree)) showed the participants of the experimental group had slightly more confidence in their answers ($M = 5{,}59$; $SD = 1{,}23$) compared to the control group ($M = 4{,}60$; $SD = 1{,}88$) in the post-test. The experimental group was less prone to guessing ($M = 2{,}59$; $SD = 1{,}46$) and filling in "I don't know" as the easiest answer ($M = 1{,}41$; SD 1,87), compared to the control group (respectively $M = 4{,}27$; $SD = 2{,}12$ and $M = 2{,}13$; $SD = 1{,}68$). Moreover, the experimental group indicated being more motivated to undertake a virtual restoration project ($M = 6{,}65$; $SD = 2{,}85$) and having more confidence in thinking they would be able to execute such a project ($M = 4{,}65$; $SD = 2{,}34$) compared to the control group (respectively $M = 5{,}20$; $SD = 2{,}24$ and $M = 3{,}47$; SD 2,26).

4.2. Usability testing

The navigating exercises in the Overview OP clearly showed one exercise most participants failed: using the references as a linking tool between Steps (Fig. 4, exercise 9: 44,4% success rate). The goal of this exercise was to interpret the information in the Overview OP, based on the references which are cited underneath the given Possibilities. For example, by regarding a specific material, and crosslinking the references with the manufacturing options, one could deduct which materials can be used in a certain manufacturing process, as these choices are not interchangeable. This exercise was to explain it's not just a pick-and-choose Overview OP, but that there are relations between the Possibilities.

The interpretation of a case workflow (ex. 10: 84,9%) and using the hyperlinks to go to the reference (ex. 8: 90,7%) were clear to everyone. The Summary table as a content table (ex. 1: 72,2%), exploration of the hyperlink of the Steps (ex. 2: 74,1%), and the exercise to critically reflect on the content (ex. 7: 74,1%) were successful for most of the participants. The first difficulty was found when the participants were asked to look for a similar case study to the one presented in the exercise (a skull which needed reconstruction) (ex.4: 50,0%). The fault here lies in the fact it was not clear the table in the Introductory text consists of the case studies (= Inventory OC) and contains the object types (skull) and colour codes for its material (bone). Also, using the references underneath the Possibilities as a benchmark for its frequency or plausibility (ex. 3: 55,6%), was not clear from the start. Moreover, the searching (ex. 5: 64,8%) and navigating (ex. 6: 59,3%) function Ctrl + *F* needed some more explanation. However, when understood, they indicated Ctrl + *F* as a practical tool to use the Overview OP.

In the Evaluation questionnaire, the same parts were subjected to the participants asking how they have used the Overview OP during the writing of their treatment proposal, to evaluate the long-term usage. The results are visualised and compared in Fig. 4 and discussed in Section 4.4.

4.3. Treatment proposal

Generally, the scores given by the four reviewers are in line with the participants' average scores during the overall CR course (Fig. 5). Some performed better, some a bit less than their average scores, but no big discrepancies were noticed, which means the task was according to their level and knowledge.

The participants demonstrated the advantages and disadvantages of using 3D technologies for their cases. By describing multiple possible methodologies, they showed insight into the process and the opportunities 3D technology offers. Although decent proposals were written, some patterns reoccurred, mostly applicable to the feasibility and estimation of the proposed methodology. These observations should be focus points during the education of using 3D technologies for CR/CH because they can be considered experiential insights only to be internalised when trying out the proposed methodologies.

- Limited or superficial attention was given to describing the post-processing steps and the virtual reconstruction phase.
- Limited critical reflection on the methodology of consulted sources and the applicability to their case.
- Limited steps to test the described methodology or to anticipate problems.
- Limited, irrelevant, or assumption-based argumentation as to why choose a certain methodology/device/material (mainly in 3D scanning and 3D printing)

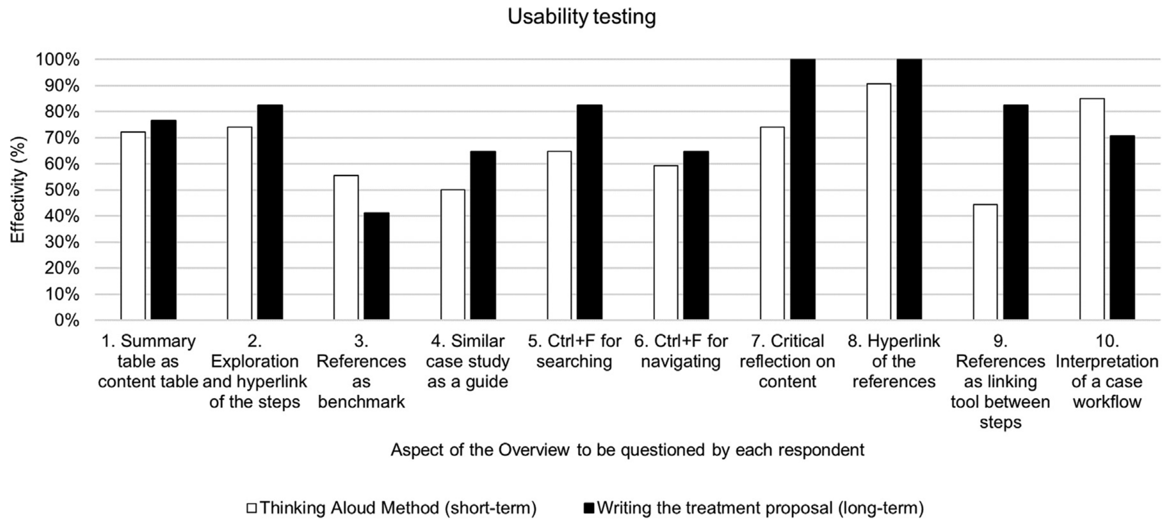

Fig. 4. User experience of the Overview OP from the participants' first experience to a more advanced experience after the experiment.

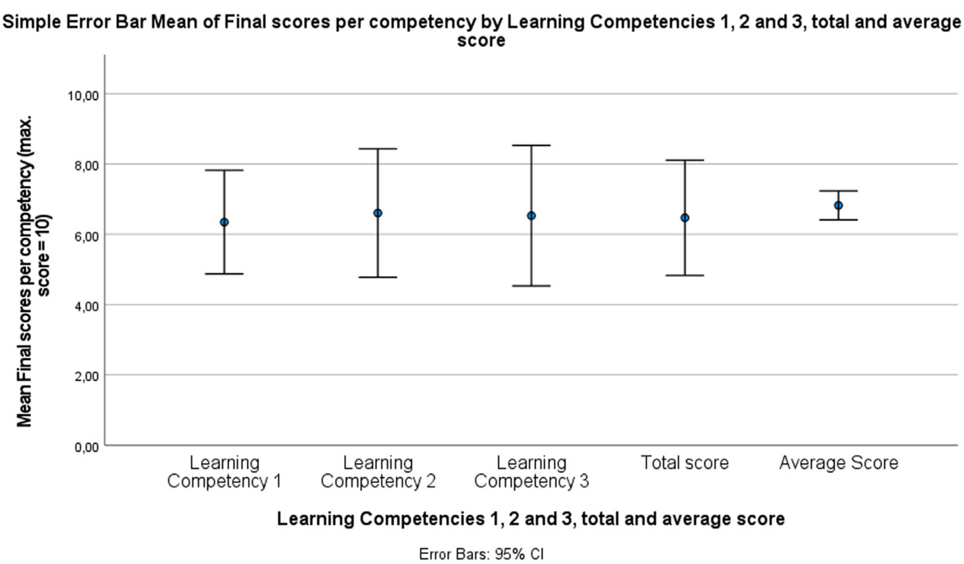

Fig. 5. Average score per learning competency and in total, next to their overall average score across the CR course.

- Limited insights on (the specifications of) the proposed devices and materials (e.g. working principle, resolution, accuracy layer thickness, the surface structure of materials, material safety)

Aspects of the learning competencies were given a score, according to Table 2, which was subsequently converted to a score out of 10, relative to their point weight. In Fig. 5, the learning competency's individual scores can be seen, next to the total and compared to the participants' average amount of points across the CR course (provided by the participants).

4.4. Evaluation questionnaire

While writing the treatment proposal, the participants indicated they used the Overview OP to gain insights into the steps in the workflow and to start with the search for information for their case study, by looking for a similar referenced case study and to quickly lookup possibilities within a Step, mostly exploring 3D scanning, virtual reconstruction and 3D printing options. They used the steps provided both as a starting point and a guide and afterwards to check if they covered all the steps in their proposal.

The participants appointed mostly the cited references in the Overview OP as a source of information (31,8% of 100%), followed by the Overview OP itself (22,6%). They also consulted online websites (14,5%) and scientific literature not mentioned in the Overview OP (10,9%). Other sources mentioned were: consulting with other students (3,2%), consulting with the first author (3,0%), other sources (personal connections, previous own reports) (2,6%), trying out 3D scanners, software, printers or other (2,4%), other types of not scientific literature not mentioned in the Overview OP (1,8%), and consult with the lab lecturer (1,2%).

The participants unanimously thought the given order of the Steps was meaningful in writing their proposal (100%). If applicable, they also followed these Steps (94,1%) and incorporated them in their proposal (76,5%). The majority found the references of the case studies to be meaningful for writing their proposal (94,1%), as well as the number of references given underneath each Possibility (70,6%). They indicated they used the references to find out the methodology of one or multiple case studies (82,4%) and reported having read these case studies (88,2%) which were, in addition, also of great help (88,2%) in writing their proposal.

It can thus be concluded that consulting similar references is a valuable source of information and the Overview OP provides the steps to order the references' workflows, which can also be considered valuable in writing a treatment proposal.

The ten parts of the Overview OP which were the subject of the usability testing were again questioned in the evaluation questionnaire. Compared to the questions during the usability testing, which are a reflection of the participants' first experience in the short-term, it now shows advanced user experience after writing the treatment proposal and therefore it gives valuable insights into the perception of the participants and effective use of the Overview OP on the long term.

Almost all aspects have an increased success rate, with the highest increase in the use of the references as a linking tool between Steps (ex. 9). While this function was the least clear during the usability testing, the feedback shows the participants did understand how to use the reference as a way to see connections in the information given in the Overview OP. Two decreases in success rate were noticed: the references as a benchmark (ex. 3) and the interpretation of a case workflow (ex. 10). Nonetheless, coming down from 84,9% success rate, the latter is still proving to be effective with a success rate of 70,6%. Exercise or aspect 3, however, does seem to be missing its functionality, as only 41,2% reported to have used the references as a benchmark.

It must be clarified that the reflection of the participants' advanced experience use is a subjective representation of the ten parts of the Overview OP. This is clear from the participants' answers to their critical reflection on the content (ex. 7), which has, along with aspect 8, the highest percentage of 100%. Yet, it was clear from the evaluation of their treatment proposals there is still a lack of insight into the feasibility of the proposed methodologies.

Many of the participants stated it was overwhelming at first, but once they got to know how the Overview OP worked, praised the organised structure, the efficiency and the time-saving aspect of consulting the Overview OP. Although the participants acknowledge this Overview OP can be a good starting point for figuring out a virtual restoration methodology, they also pointed out the difficulty in terminology and the amount and complexity of the information given (too technical, too much jargon) without having prior knowledge of 3D technologies. Making grounded choices applicable to their cases proved difficult, as the Overview OP only provides the possibilities and not reasons to choose one option and not another. Moreover, the said benchmark of the number of references is not always a benchmark for quality or suitability but can be a benchmark for, for example, the availability or price of a certain method or material. Reasoning for these choices should be found in the publication of the cases themselves, as these choices are highly material, object, device and product-related.

Next, suggestions were given by the surveyor, which might be an added value for (the use of) the Overview OP. The participants were asked to which extent these suggestions would be useful. They indicated the addition of general information on the various steps (for example references specifically on 3D scanning) as most useful (82,4%), along with pop-up texts with warning signs for questionable possibilities (for example, unstable plastic 3D printing materials) (82,4%) and a system for filtering case studies based on year, material, object type,… (82,4%). The following suggestions would also be considered an added value: an online accessible version of the Overview OP (for example in which the addition of new cases would be possible) (76,5%), pop-up text to give information on all of the possibilities (76,5%), a visual summary of the introduction text (for example in an infographic) (70,6%) and a breakdown of mandatory and optional choices (70,6%). To a lesser extent were the participants requesting party for a fully written-out textbook with all of the mentioned possibilities (52,9%), more exemplary questions next to the modules (47,1%), breakdown of choices and other information (like "detailed descriptions", "general steps") (47,1%), images of the referred cases (41,2%) and images of the steps in the process of restoration (23,5%).

Besides the suggested additions, the participants were free to make suggestions themselves. They mostly suggested adding more information (literature, websites, movie clips) about 3D scanning, 3D modelling and 3D printing to gain background knowledge on the virtual steps, besides more detailed information on specific devices.

The participants also stated the need for specific references on the material stability of 3D printing materials and their compatibility with organic objects, as this is indeed a major concern in applying 3D technologies for loss compensation.

The participants pointed out that the referenced cases did not prove equally applicable to their cases. For some cases, mostly the painting frames and textiles cases, limited information is provided in the Overview OP. This has its origin in the fact that these material objects' treatments are generally less suitable for using 3D technologies. However, adding more case studies, as they suggested, might fill this gap. Finally, some suggestions were made to ameliorate the layout, including making the hyperlinks colour-coded with the material types as presented in the Inventory OC.

Next, on a scale of 0 to 10, the participants were asked to rate each part of the Overview OP as either being meaningful (=10) or unnecessary (=0). While some parts were defined to be more meaningful than others, all the parts of the Overview OP scored above average (61,2% to 92,4%). Therefore, all parts will be preserved in the adaptation. Generally, the "Traditional restoration steps" and the defined "Milestones" showed more scattered opinions, while more consensus on the meaningfulness was found in the steps involving 3D technologies, with "Choice of material" and "Choice of manufacturing" as the most meaningful parts. The distribution is visualised in a box-and-whisker graph in Appendix E.

Finally, by indicating descriptive words from a list of the Microsoft Product Reaction Cards a quantitative image was formed of how the participants perceived the Overview OP. 70,6% of the participants indicated the Overview OP as being organized, followed by being useful, helpful and timesaving (each 52,9%), being understandable, relevant, accessible (each 47,1%), professional (41,2%), efficient, clear, innovative and comprehensive (each 35,3%). Negative experiences included the Overview OP being overwhelming (35,3%), complex (29,4%), too technical (23,5%) and confusing (11,8%). The complete list with results can be found in Appendix F.

Overall, these results suggest that the Overview OP was positively received and can serve as an initial resource for acquiring basic information about a virtual restoration workflow. Users can then delve deeper into the mentioned references or explore other scientific and non-scientific sources. While the Overview OP has a learning curve, many of its aspects demonstrated a high success rate.

5. Revision of the Overview of possibilities

In this section, efforts have been made to enhance the aspects of the Overview OP that were deemed less successful. Adaptations were guided by the suggestions provided in the evaluation questionnaire and the feedback received during and after the experiments. Minor changes, including adjustments in wording and rearrangements of Modules and Possibilities, have not been discussed here but can be observed by comparing the initial and updated versions (Appendix A) of the Overview OP.

5.1. Infographic

Participants noted that the Overview OP was initially overwhelming, and there was uncertainty about how to navigate its various components. To address this, a visual summary demonstrating how to use the Overview OP has been created in the form of an infographic. The boxes surrounding the schematic example of the Overview OP clarify the same ten aspects evaluated in the usability testing (Section 3.2). Boxes with question marks have been added to provide explanations of the Summary table and the Inventory OC.

5.2. More information

To address the lack of context or background knowledge and meet the demand for more specific information regarding the stability of 3D printing materials, introductory information and further reading suggestions (including literature, books, charters, standards, theses, and websites) have been provided under the headings of Phases of Decision-making, Research, Data acquisition, Virtual reconstruction, and Physical reconstruction. These sources have been placed in the most relevant phase (for instance, sources related to research on 3D printing materials are now located under the Research Phase but are also pertinent to the Physical Reconstruction Phase). It's important to note that these sources serve as stepping stones, as only recent references have been included, and it is impossible to cover all relevant information on each aspect comprehensively.

5.3. Research step

Acknowledging the identified need for more information on the material properties and stability of 3D printing materials, particularly concerning their suitability for organic materials, an analysis of all cases was conducted to identify the applied research methods. Consequently, various Research Modules were defined, each serving a specific purpose (e.g. material properties analysis, ageing, imaging, chemical composition analysis, restoration treatment tests, force analysis, shape analysis, colour analysis) along with their Possibilities outlining specific techniques (e.g. microscopy, XRF, Oddy testing, FEM) or subgoals (e.g. authentication, comparisons, cross sections). It's crucial to note that the representation of the mentioned research techniques is not exhaustive, as it only encompasses what has been found in the examined case studies. Future case studies may explore additional research purposes and techniques beyond the ones presented here.

Additionally, the Possibilities categorised within the Research Step often serve as means to evaluate or verify the reconstruction, the materials used, or the applied methodology. Therefore, these references are also linked in the Verification Steps where applicable.

5.4. Literature review 2020–2023 update

The participants highlighted that the information available in the initial version of the Overview OP had limited applicability for specific cases when writing their treatment proposals. To address this, a new literature review was conducted, covering the period from 2020 to 2023. This review yielded 27 additional references, incorporating 28 new cases and leading to a slight diversification in material types compared to the first literature review. Notably, the updated content now includes a case related to a painting, several moulding cases, and another involving a painting frame, which would have been beneficial for the participants. Textile cases remain absent.

Table 3
Cases' references found in the literature update, along with the case material, object specification and missing part to be restored.

	Case in Overview OP	Ref.	Authors	Material	Object	Missing part
Journal articles	58	[29]	Acke et al., 2023	Ceramics	Figurine	Cuff, hand, violin
	59	[47]	Akkas, Guzel, 2022	Wood	Chair	Connection piece
	60	[48]	Aura-Castro et al., 2021	Glass	Bowl	Foot and body
	61	[22]	Bahrampoor, Karimy, 2016	Glass	Beaker	Rim, body, handle
	62	[49]	Calî et al., 2021	Mural	Moulding	Decorative element
	67	[50]	Higueras et al., 2021	Mural	Moulding	Embossed fragment
	70	[51]	Liu et al., 2022	Ceramics	Bowl	Rim and body
	72	[52]	Papas et al., 2023	Ceramics	Plate	Majority fragment
	73	[53]	Parfenov et al., 2023	Metal	Fence	Star ornament
	75	[27]	Rizzo et al., 2023	Wood	Ciborium	Columns
	76	[54]	Shin and Wi, 2020	Ceramics	Bowl, dish	Rim fragments
	79	[55]	Torres-González et al., 2022	Mural	Decorative element	High relief
	83	[56]	Vazzana et al., 2022	Teeth	Human teeth	Halves
Conference proceedings (Including oral presentations and posters)	63	[57]	Conceição et al., 2022	Ceramics	Dish	Rim and body fragments
	64	[58]	De Vos et al., 2022	Ceramics	Vessel	Rim and body fragment
	65	[23]	Haynes et al., 2018	Bone	Goose skeleton	Wing and foot digits
	66	[59]	Henriques et al., 2021	Wood	Painting frame	Rosette
	71	[60]	Oliveira et al., 2021	Ceramics	Relief tile	Spike and sceptre
	74	[61]	Peters, 2021	Stone	Architectural ornament	Tower
	77	[24]	Stojković, 2016	Ceramics	Tulip vase	Pyramid elements
	78	[62]	Teixeira, 2022	Ceramics	Tureen	Handle
	81	[25]	Vanhellemont et al., 2016	Stone	Architectural ornament	Pinnacle
Websites and magazine articles	57	[63]	3D ArcheoLab, 2021	Ceramics	Statue	Body fragments
	68	[64]	Lincoln Conservation, 2023a	Paper	Ceiling	Panels
	69	[65]	Lincoln Conservation, 2023b	Ceramics	Figurine	Arms, textile fragments
	80	[35]	Ulbricht, 2022	Ceramics	Vase	Lip fragment
	80	[35]	Ulbricht, 2022	Ceramics	Vase	Elephant tusk
	82	[66]	Van Oudheusden, Duggins, 2019	Painting	Painting canvas	Brush strokes
	84	[67]	Walen, Jooshesh, 2020	Bone	Dinosaur skull	Fragments

The newly discovered references are listed in Table 3. Some of these references date back to before 2020, but were overlooked in the initial review, or possibly were only recently made available online [22–25]. Notably, the articles of Rizzo et al. and Fico et al. [26,27] handle the reconstruction of the columns of the same ciborium. While the article of Fico et al. focusses on the comparison of PETG and pine wood CNC-milling for reconstruction, the article of Rizzo et al. focusses on the effective application of a 3D printed reconstruction. Only the latter was included as it discusses the process towards the physical restoration. Likewise, the articles from Acke et al. [28,29] address different parts of the same figurine, utilising varied methodologies to fill the losses with 3D technologies. Consequently, both articles were incorporated due to the application of different techniques for distinct lacunae.

The case presented by De Vos et al. [30] is incorporated as a poster presented at the 6th Interim Meeting of the ICOM-CC Glass and Ceramics Working Group, 9–11 November 2022, Lisbon, Portugal, but the full details are described in the forthcoming conference proceedings of the 9th International EuroMed conference on Digital Heritage, 7–11 November 2022, Nicosia, Cyprus [31].

Lastly, it must be mentioned that case 14 in the Overview OP is a conference presentation, of which only an abstract was found online, but was complemented by the Master thesis of Dafne Cimino, in which the case of the cherub's missing wings was further described. In her thesis, she executed analytical research which is also incorporated in the Overview OP. Other theses were not included in the Overview OP, but case 14 must be seen as a combination of both works [32,33].

The included cases were read and analysed in Nvivo 12 Pro and categorised in the existing codes of the first version of the Overview OP. Where and if applicable, new codes (Modules and Possibilities) were added and existing ones were altered.

Observations highlighted that the recently discovered cases predominantly feature ceramic objects (13 cases). The remaining cases include objects made from bone and teeth (3), murals (3), glass (2), metal (1), stone (1), painting (1), and paper (1). In the initial literature review [12] the emphasis was primarily on (the comparative study of) the data acquisition phase and less on the 3D printing materials. However, the focus has now shifted towards a more research-oriented verification of the applied methodologies, encompassing many comparisons of reconstruction materials.

In total, numerous interesting research articles were discovered, which present innovative approaches with relevant applications on the use of 3D models, and are as such also valuable resources. However, they were excluded from the review due to their focus not being on loss compensation but rather replication, virtual restoration, researching restoration hypotheses, material exploration, and experimenting with new manufacturing methods. When applicable, they have been included as additional information in the headings of the Phases as explained in Section 5.2. In the following paragraph, a few examples are provided.

Abel et al.'s research [34] delves into optimising the sintering distortion of Material Extrusion (MEX) printed ceramics and discusses an 18th-century porcelain vase as a case study, although their methodology wasn't ultimately applied. Nevertheless, the same vase and its treatment are briefly mentioned by Ulbricht [35], hence it has been included in the Overview OP. Colonneau et al. [36] researched and simulated two approaches for restoring concrete columns, but didn't implement them in an actual restoration case. Gänsicke and Lang [37] reconstructed an automaton, creating a 3D model to simulate its parts; however, it's unclear if or how the 3D model assisted in the physical reconstruction of the system. Lv and Fu's [38] publication was excluded because it pertained to porcelain 3D printing of a virtually restored replica, not involving physical restoration. Makris et al. [39] extensively researched the digital restoration of a wax figurine, although the physical restoration was not yet conducted but is planned for future work.

The case by Sterp Moga et al. [40] describes the virtual anastylosis of a fragmented wax anatomical model, along with 3D modelling and digital manufacturing of auxiliary structures to support its conservation treatment. This included tensile and bending tests of the 3D printing materials to ensure mechanical safety during treatment. Măruţoiu et al. [41] used a 3D printed support as assistance during physical reassembly of pottery fragments. Angheluță et al. [42] explored the preparation stages and restoration hypothesis of a bronze vessel, incorporating virtual anastylosis and reconstruction. Alfio et al. [43] studied the structural stability of a bronze statue using a Scan to FEM approach. Finally, articles focussing on providing secondary or supporting structures for fragmentary objects [44–46] often employ similar digital modelling strategies and are therefore beneficial during the Virtual reconstruction Phase.

5.5. Filter cases on material, object, missing parts and validation (peer-review and authors' background)

To make informed, qualitative, and grounded choices, critical reflection on the given possibilities in the referenced cases is crucial.

Traits such as material, object and definition of the missing part, significantly influence if the object is suitable for virtual restoration. Based on these traits, users can find similar case studies in the Inventory OC by filtering on parameters like "material type," "material specification," "object type," "object specification" and "missing parts". General information such as "author alphabetically," "year" and "title of the publication" is also available for filtering.

Additionally, a filter for validation is provided in the Inventory OC. A first distinction is made on the peer-reviewed status of the publication, categorised into journal papers, conference output (paper, oral or poster presentation), magazine articles or online websites). Peer-reviewed publications (journal papers and conference papers) generally uphold higher scientific rigour, often supporting their rationale with other literature, analytical methods or experiments. They are typically more comprehensive in documenting their workflow. However, non-peer-reviewed publications found online and in magazines adopt a broader approach to reporting, meant for a wider audience. It's important to note that the lack of peer-review does not necessarily indicate that these cases are less successful or reliable. Thus, the peer-reviewed subdivision is not definitive for the ethical and scientific-based rationale of the treatment and therefore a second level of validation was introduced based on the background of the authors (Table 4). The background of the authors is a representation of the successful collaboration that took place, and it can be noticed that when the first author is someone with a CR (or CH) background (generally the most involved person or the one who executes the most of the project), ethical guidelines in CR work are more respected compared to when the first author has a 3D, technical or engineering background. On the other hand, if the authors only have a technical background, CR guidelines (context on the artefact and decision-making) are sometimes completely disregarded. Conversely, authors solely with a CR/CH background might lack necessary or accurate information regarding the application of 3D technologies.

In the Inventory OC, the background of the first author is specified, along with the backgrounds of other authors, providing insights into the collaboration that took place. Table 4 provides a general view of these backgrounds. The mention of "CR+3D" can be considered a new background, signifying practices or research institutes possessing an intertwined knowledge of restoration methodologies combined with 3D technologies, indicating their expertise in both domains.

Table 4
The indicated amount of authors per background.

Field/organisation	Company or practice	Research institute or university	Museum	Government
CH/CR (Incl. art, art history, archaeology, conservation-related professions)	20	41	21	–
3D (Incl. fab labs, engineering, mathematicians, product design, IT and visual media-related professions)	14	35	–	–
CR+3D (Professionals actively combining CR work with 3D methodologies)	6	4	–	–
Architecture	3	6	–	–
Natural sciences (Incl. chemistry, radiology, geology)	–	4	1	–
Other	–	–	–	2

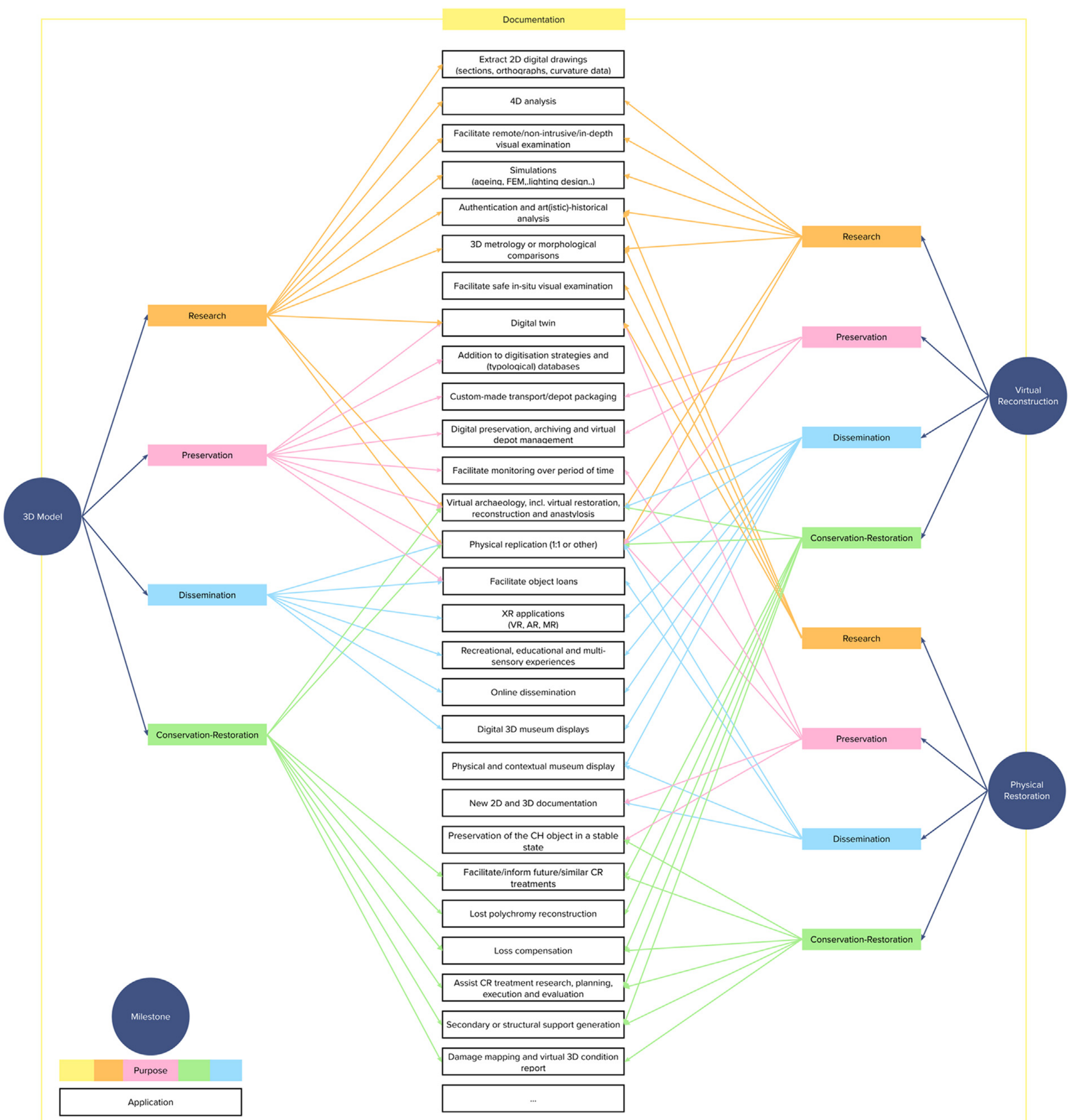

Fig. 6. Other purposes related to documentation, research, preservation, dissemination and conservation-restoration of CH objects, which are unlocked by achieving a Milestone (obtaining a 3D model, a virtual reconstruction or a finished physical restoration), and which can have academic, educational, curatorial or commercial motives.

5.6. Pop-up info

To offer additional context, examples or clarification (e.g. warning signs) pop-up text appears when hoovering over the sticky note symbol in the Overview OP PDF.

5.7. Warning signs

Warning signs and accompanying clarifications in pop-up notes are placed next to more questionable polymers used in 3D printing. However, it is important to note that a definitive distinction of a good or bad 3D printing material cannot be made solely based on its suitability for direct integration. This is highly dependent on the specific composition of the materials. It is always recommended to conduct in-house testing to ensure compatibility for the intended application.

5.8. Lay-out

The overwhelming impression indicated by the participants was amplified by the busy colour scheme, the small font and therefore limited readability. The overall look is simplified, the font is sized up and a calmer colour scheme is applied.

5.9. Colour-coding

To enhance the aspect “References as a benchmark”, references are now colour-coded by material type, such as demonstrated in the Inventory OC. This visual distinction makes it clearer which references are more prevalent under each Possibility, aiding users in their analysis and understanding of the provided information.

5.10. Milestones

The participants found the Milestones less necessary or meaningful, and indeed, not much attention was given to them in the first version of the Overview OP. However, it’s crucial to recognize that Milestones represent a vital aspect of the virtual restoration workflow. They maximize the potential of the achieved outcome and unlock other applications of the use of a 3D model, a virtual reconstruction, or a physical restoration. These applications can serve purposes such as research, preservation, dissemination, or conservation-restoration. They also have an overarching objective of documentation and can simultaneously fulfil various academic, educational, curatorial, or commercial motives.

A scheme outlining the possible applications of these three milestones is presented in Fig. 6. Many of these applications have been mentioned in the introduction or related work sections of the literature review publications.

5.11. Online version

To ensure accessibility for researchers, CR practitioners, educators and students, and to make the translation from scientific output to practical resources, the Overview OP, the Inventory OC and previously published Mind maps for decision-making [12] are presented in an online environment as three tools, designed to assist in using 3D technologies for CR projects. Ideally, The Overview OP would be an accessible, updateable and interactive online tool, where case-specific workflows could be highlighted, and coded text fragments would be visible. However, due to limited technical and economic resources, an online static version of the Overview OP and Inventory OC is the most feasible option at present. This version is hosted on the collaborative platform Mural. In the future, the Inventory OC could be updated to include new case studies, pending a possible future update of the Overview OP. To facilitate feedback and submissions of new cases, a suggestion box is provided in Mural using a Google Form[1]. This approach ensures a collaborative and evolving platform for the CR community.

5.12. Revisions not included in this version

Certain improvement suggestions fell outside the scope of this revision as they require additional resources and necessitate more significant structural changes or programming. These suggestions are valuable and would enhance the usability and effectiveness of the Overview OP, while making it future-proof:

- A breakdown of mandatory and optional choices: To prevent guessing or random selection from the Overview OP. However, The Steps “Choice of manufacturing” and “Choice of material” were renamed to “Manufacturing method” and “Reconstruction material” to avoid giving the impression that users could arbitrarily combine materials and manufacturing methods.
- A clear linear workflow per case: To facilitate the easy interpretation of each case’s workflow.
- An updateable online, interactive version of the Overview OP: As discussed in 5.11

6. Conclusion

To inform conservation-restoration (CR) practitioners about the possibilities of the use of 3D technologies in loss compensation for cultural heritage (CH) objects, and present them with ample work performed by other restorers, an educational process worksheet was created in the form of an overview. This *Overview of possibilities* (Overview OP) serves as a platform for disseminating valuable research sources (incl. studies on data acquisition, virtual reconstructions,...) while also offering a comprehensive perspective on the complete virtual restoration workflow, aiming for the physical restoration of CH objects. The Overview OP is constructed through qualitative analysis of a literature review of executed loss compensation case studies. In the presented workflow, both traditional and virtual Phases are defined, comprising Steps and further divided into relevant Modules and Possibilities mentioned in the cases.

Given its educational motive, the initial version of the Overview OP underwent testing, involving third-year bachelor students enrolled in the practical restoration course at the University of Antwerp. Testing involved a pre and post-test to assess the improvement in the participants’ understanding of 3D technologies after consulting the Overview OP. Usability testing was conducted using a Thinking Aloud protocol, to obtain initial feedback on the structure and the components of the Overview OP. Subsequently, the participants were tasked with consulting the Overview OP to write a treatment proposal for a case study of their own.

The experimental set-up showed the Overview OP can effectively assist restorers in gathering information and gaining an overall understanding of the virtual restoration workflow. However, it was noted that the first impression could be overwhelming and using the Overview OP does require a learning curve. Based on the feedback, the Overview OP was refined, and new case studies were added by extending the literature review to cover the period of 2020 to 2023.

Due to the time-sensitive nature of this collection of work, it’s possible that executed cases may have been overlooked, also because of language barriers, different keywords, or publication in non-academic magazines. Readers are encouraged to inform the first author of any executed cases.

[1] As hyperlinks to websites may become obsolete in the future, alternatively, the first author can be contacted at the provided email address

The presented Overview OP can be seen as a tool to assist the CR practitioner throughout the process of knowledge generation, decision-making, managing and performing digital tasks, when applying 3D technologies for restorative interventions involving loss compensation on CH objects. A second tool to inform restorers on executed cases encompasses the *Inventory of cases* (Inventory OC) which is essentially a list of the case studies in the Overview OP, with the flexibility to filter cases based on criteria such as authors, year, material type and specification, object type and specification, missing part, peer-review status and background of the authors. A third tool consists of previously published *Mind maps for decision-making*. These three tools are now consolidated in an online environment, forming a 3D Restoration Toolbox. This platform enables interested professional or emerging CR practitioners to inform themselves on the advantages, disadvantages, concerns and practical applications of the use of 3D technologies within CR work.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT 3.5 and Deepl write in order to spell-check and review written text fragments on used grammar and vocabulary. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Lien Acke: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Visualization, Writing – original draft, Writing – review & editing. **David Corradi:** Methodology, Validation, Formal analysis, Resources, Visualization, Writing – review & editing. **Jouke Verlinden:** Supervision, Writing – review & editing.

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Appendices

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.culher.2024.01.013.

- Appendix A: **Overview of possibilities**, PDF document
- Appendix B: **Inventory of cases**, Excel document
- Appendix C: List of statements used in the pre and post-test
- Appendix D: Protocol used during usability testing via TAM
- Appendix E: Meaningfulness of the parts of the Overview OP
- Appendix F: Microsoft Product Reaction Cards

References

[1] The London Charter, The London Charter for the Computer-Based Visualisation of Cultural Heritage, 2009, pp. 1–13 http://www.londoncharter.org/fileadmin/templates/main/docs/london_charter_2_1_en.pdf.

[2] International Forum of Virtual Archaeology, Principles of Seville: international principles of virtual archaeology, Virtual Archaeol. Rev. (2011), doi:10.1145/3230678.

[3] L. Di Angelo, P. Di Stefano, L. Fratocchi, A. Marzola, An AHP-based method for choosing the best 3D scanner for cultural heritage applications, J. Cult. Herit. 34 (2018) 109–115, doi:10.1016/j.culher.2018.03.026.

[4] I. Budak, Z. Santosi, V. Stojakovic, D.K. Crkvenjakov, R. Obradovic, M. Milosevic, M. Sokac, Development of expert system for the selection of 3D digitization method in tangible cultural heritage, 26 (2019) 837–844. https://doi.org/10.17559/TV-20180531120300.

[5] S. Wefers, A. Karmacharya, F. Boochs, Development of a platform recommending 3D and spectral digitisation strategies, Virtual Archaeol. Rev. 7 (2016) 18–27, doi:10.4995/var.2016.5861.

[6] H. Rahaman, E. Champion, To 3D or not 3D: choosing a photogrammetry workflow for cultural heritage groups, Heritage 2 (2019) 1–16, doi:10.3390/heritage2030112.

[7] Europeana Network AssociationTask Force Report: 3D Content in Europeana Task Force, 2020.

[8] A. D'Andrea, K. Fernie, CARARE 2.0: a metadata schema for 3D cultural objects, in: Proc. Digit. 2013 - Fed. 19th Int'l VSMM, 10th Eurographics GCH, 2nd UNESCO Mem. World Conf. Plus Spec. Sess. FromCAA, Arqueol. 2.0 Al, 2013, pp. 137–143, doi:10.1109/DigitalHeritage.2013.6744745. 2.

[9] 3D ICONS, 3D-ICONS: 3D digitisation of icons of European architectural and archaeological heritage, (n.d.). http://3dicons-project.eu/.

[10] European CommissionStudy Report on Quality in 3D Digitisation of Tangible Cultural Heritage - Mapping Parameters, Formats, Standarts, Benchmarks, Methodologies and Guidelines, 2022 https://digital-strategy.ec.europa.eu/en/library/study-quality-3d-digitisation-tangible-cultural-heritage accessed April 13, 2023.

[11] R. Scopigno, P. Cignoni, M. Callieri, F. Ganovelli, G. Impoco, P. Pingi, F. Ponchio, I. Isti, Using Optically Scanned 3D Data in the Restoration of Michelangelo ' s David, 2001.

[12] L. Acke, K. De Vis, S. Verwulgen, J. Verlinden, Survey and literature study to provide insights on the application of 3D technologies in objects conservation and restoration, J. Cult. Herit. 49 (2021) 272–288, doi:10.1016/j.culher.2020.12.003.

[13] O. Bik, J. Bouwens, Bridging the knowledge gap between academia and practice: how research can help develop the auditing profession (vice versa), Maandbl. Voor Account. En Bedrijfsecon 92 (2018) 221–228, doi:10.5117/mab.92.30360.

[14] T. Ross-hellauer, J.P. Tennant, V. Banelyte, E. Gorogh, D. Luzi, P. Kraker, L. Pisacane, R. Ruggieri, E. Sifacaki, M. Vignoli, Ten simple rules for innovative dissemination of research, PLOS Comput. Biol. (2020) 1–12, doi:10.1371/journal.pcbi.1007704.

[15] P. Kirschner, J.J.G. Van Merriënboer, Ten steps to complex learning: a new approach to instruction and instructional design, in: 21st Century Educ. A Ref. Handb., 2008, pp. 244–253.

[16] P. Kirschner, I.G.J.H. Wopereis, Mindtools for teacher communities: a European perspective? Technol. Pedagog. Educ. 12 (2003) 105–124, doi:10.1080/14759390300200148.

[17] P. Kirschner, N. Davis, Pedagogic benchmarks for information and communications technology in teacher education, Technol. Pedagog. Educ. 12 (2003) 125–147, doi:10.1080/14759390300200149.

[18] L. Acke, S. Verwulgen, K. De Vis, J. Verlinden, Compiling a digital toolbox : the use of 3D technology for the restoration of intricate artworks, in: Proc. Recent Adv. Glas. Ceram. Conserv. 2019, ICOM-CC ICON Interim Meet. Glas. Ceram. Work. Group, 5-7 Sept. 2019, 2019, pp. 211–216. London, UK.

[19] T. van Gog, F. Paas, J.J.G. van Merriënboer, P. Witte, Uncovering the problem-solving process: cued retrospective reporting versus concurrent and retrospective reporting, J. Exp. Psychol. Appl. 11 (2005) 237–244, doi:10.1037/1076-898X.11.4.237.

[20] J.P. Brown, R.D. Martin, Restoration by other means: CT scanning and 3D computer modeling for the re-restoration of a previously restored skull from the Magdalenian era, in: Objects Spec. Gr. Postprints, 2014, pp. 81–101.

[21] ScienceDirectProduct Reaction Cards, Elsevier, 2023 https://www.sciencedirect.com/topics/computer-science/product-reaction-card accessed September 27, 2023.

[22] S. Bahrampoor, H. Karimy, Using three dimensional printer for reconstruction of historic glass objects (autotranslated), J. Conserv. Archit. Iran 6 (2016) 115–126 https://mmi.aui.ac.ir/article-1-376-en.html.

[23] C. Haynes, J. Sybalsky, F. Ritchie, 3D printing for casting proportional replicas in the conservation of articulated skeletons, in: AIC Annu. Meet. 2018 - Objects Spec. Gr. Postprints, 2018, pp. 31–48.

[24] D. Stojković, The use of 3D scanning and printing in the conservation and restoration treatment of delft blue-and-white tulip pryamids, Poster Present. ICOM-CC Work. Gr. Glas. Ceram. Interim Meet, 2016 25-26 May 2016Wroclaw, Pol. https://www.hetblauwepaard.nl/single-post/2016/05/30/use-of-3d-scanning-and-printing-in-conservation-and-restoration-treatments-of-delft-blue .

[25] Y. Vanhellemont, M. de Bouw, L. Dekeyser, S. Dubois, S. Vermeir, P. Van Damme, J.-A. Van der Have, in: Application of Digital Technologies in the Restoration of Historic Buildings and Heritage Objects, EuroMed, 2016, p. 3, doi:10.1007/978-3-319-48974-2. Part II, LNCS 10059, 2016.

[26] D. Fico, D. Rizzo, F. Montagna, C.E. Corcione, Fused Filament fabrication and computer numerical control milling in cultural heritage conservation, Materials (2023).

[27] D. Rizzo, D. Fico, F. Montagna, R. Casciaro, C.Esposito Corcione, From virtual reconstruction to additive manufacturing: application of advanced technologies for the integration of a 17th-century Wooden Ciborium, Materials 16 (2023), doi:10.3390/ma16041424.

[28] L. Acke, K. De Vis, T. De Kock, E. Indekeu, J. Van Goethem, S. Van Akeleyen, M. Cornelis, J. Verlinden, S. Verwulgen, Treatise of digital reconstruction and restoration of lace porcelain, in: M. Ioannides, E. Fink, R. Brumana, P. Patias, A. Doulamis, J. Martins, M. Wallace (Eds.), Digit. Herit. Prog. Cult. Herit. Doc. Preserv. Prot. 7th Int. Conf. EuroMed 2018, Oct. 29-November 3, 2018, Nicosia, Cyprus, EuroMed, 20, Springer, Cham, 2018, pp. 15–26, doi:10.1007/978-3-030-01762-0_2.

[29] L. Acke, J. Vleugels, M. Kovač, J. Verlinden, Comparative study of colour stability and shape retention: from virtual reconstruction to physical restoration of a

porcelain figurine, Digit. Appl. Archaeol. Cult. Herit. (2023), doi:10.1016/j.daach.2023.e00280.
[30] R. De Vos, S. Bauvois, J. Verlinden, L. Acke, Filling in the gaps : application of 3D technology to create a detachable fill for an earthenware skyphos, in: R. Gridley, V. Schussler (Eds.), Recent Adv. Glas. Ceram. Conserv. 2022 - 6th Interim Meet. ICOM-CC Glas. Ceram. Work. Gr. - 9-11 Novemb. 2022, 2022, p. 314. Lisbon, Port..
[31] R. De Vos, S. Bauvois, J. Verlinden, L. Acke, Application of 3D technology to create a detachable fill for an earthenware skyphos, Digit. Herit. Prog. Cult. Herit. Doc. Preserv. Prot. 9th Int. Conf. EuroMed 2022, 7-11 Novemb. 2022, Nicosia, Cyprus, 2022.
[32] A. Braghieri, S. Capetta, D. Cimino, M. Mambrin, V. Moratti, T. Poli, G. Rollo, Utilizzo Della Stampante 3D Per La Ricostruzione Di Parti Mancanti Nel Restauro Di Due Sculture lignee, in: Restauro Nell'era Della Fabbr. Digit, 2016 Nov 4, 2016, Parma, Oral presentation.
[33] D. Cimino, Characterization of Polymeric 3D Printing Filaments For Application in the Conservation Field, Università degli Studio di Torino, 2016.
[34] J. Abel, S. Tiwari, M. Reichel, U. Scheithauer, Reducing the distortion in particle filled material extrusion (MEX)-based additive manufacturing (AM) by means of modifying the printing strategy, Ceramics (2022) 1225–1241.
[35] H. Ulbricht, Der gedruckte Rüssel - Ein Elefantenrüssel ist die erste gedruckte Ergänzung aus Porzellan (autotranslated), Museum Aktruell (2022) 44–48.
[36] T. Colonneau, S. Chenafi, A. Mastrorilli, Digital intervention methodologies and robotic manufacturing for the conservation and the restoration of 20th-century concrete architecture damaged by, in: ECAADe 40 - Educ. Res. Comput. Aided Archit. Des. Eur., 2022, pp. 197–206. https://papers.cumincad.org/data/works/att/ecaade2022_170.pdf.
[37] S. Gänsicke, R. Lang, The reanimation of a renaissance automaton: Diana and Stag at the museum of fine arts, Boston, ICOM-CC Work. Gr. Met. Interim Meet. Helsinki, Finl., 2019.
[38] J. Lv, J. Fu, Digital restoration and 3D printing of porcelain - a case study of double-ear clashing color vase with lotus design, J. Genet. Eng. Biotechnol. Res. 5 (2023) 14–19.
[39] D. Makris, C. Sakellariou, L. Karampinis, Emerging materiality through dynamic digital conservation, Digit. Appl. Archaeol. Cult. Herit. 23 (2021) e00198, doi:10.1016/j.daach.2021.e00198.
[40] E. Sterp Moga, A. Sánchez-Ortiz, Ó. Hernández-Muñoz, 3D printing of molds for the creation of facsimiles and volumetric reintegrations in wax anatomical sculptures, Herit. Sci. 10 (2022) 1–17, doi:10.1186/s40494-022-00838-8.
[41] C. Măruţoiu, I. Bratu, M.I. Ţiplic, V.C. Măruţoiu, O.F. Nemeş, C. Neamţu, A. Hernanz, FTIR analysis and 3D restoration of Transylvanian popular pottery from the XVI-XVIII centuries, J. Archaeol. Sci. Rep. 19 (2018) 148–154, doi:10.1016/j.jasrep.2018.02.044.
[42] L.-M. Angheluță, O. Țentea, A. Dozsa, Virtual reconstruction and restoration of an uncommon bronze vessel from the Mălăiești Roman fort, Cercet. Arheol. 29 (2022) 245–258 https://cercetari-arheologice.ro/wp-content/uploads/2022/07/ca29_1_12_Angheluta.pdf.
[43] V.S. Alfio, D. Costantino, M. Pepe, A.R. Garofalo, A geomatics approach in scan to FEM process applied to cultural heritage structure: the case study of the "Colossus of Barletta, Remote Sens. 14 (2022), doi:10.3390/rs14030664.
[44] E. Betti, S. Ferucci, The reconstruction of three archaeological glass vessels from the monastery of Santa Chiara, Padua, in: ICOM-CC Work. Gr. Glas. Ceram. Interim Meet. 9-11 Novemb. 2022, Lisbon, Port, 2022, pp. 247–252.
[45] F. Raco, From Survey to Integrated Digital Documentation of the Cultural Heritage of museums: a Protocol for the Anastylosis of Archaeological Finds, SSRN, 2023, doi:10.2139/ssrn.4379421.
[46] L. Barbieri, F. Fuoco, F. Bruno, M. Muzzupappa, Exhibit supports for sandstone artifacts designed through topology optimization and additive manufacturing techniques, J. Cult. Herit. 55 (2022) 329–338, doi:10.1016/j.culher.2022.04.008.
[47] G. Akkas, T.A. Guzel, Strength of A Chair renovated with additive production systems and reverse engineering approach, Eur. J. Sci. Technol. (2022) 1150–1155, doi:10.31590/ejosat.1054613.
[48] E. Aura-Castro, C. Díaz-Marín, X. Mas-Barberà, M. Sánchez, E. Vendrell Vidal, Characterization of 3d printing filaments applied in restoration of sensitive archaeological objects using rapid prototyping, Rapid Prototyp. J. 27 (2021) 645–657.
[49] M. Calì, S.M. Oliveri, P. Calì, R. Ambu, A NURBS-based solid modeling to enhance rapid prototyping in the restoration of decorative elements, Int. J. Interact. Des. Manuf. 15 (2021) 129–132, doi:10.1007/s12008-020-00741-1.
[50] M. Higueras, A.I. Calero, F.J. Collado-Montero, Digital 3D modeling using photogrammetry and 3D printing applied to the restoration of a Hispano-Roman architectural ornament, Digit. Appl. Archaeol. Cult. Herit. (2021) 20, doi:10.1016/j.daach.2021.e00179.
[51] S. Liu, Y. Tu, X. Wang, B. Qin, Z. Xie, Y. Zhang, H. Zhang, D. Hu, Transparent reversible prosthesis, a new way to complete the conservation–restoration of a Black Ding bowl with application of 3D technologies, Herit. Sci. 10 (2022) 1–14, doi:10.1186/s40494-022-00646-0.
[52] N. Papas, K. Tsongas, D. Karolidis, D. Tzetzis, The integration of 3D technologies and finite element analysis (FEA) for the restoration of an ancient terra sigillata plate, Digit. Appl. Archaeol. Cult. Herit. 28 (2023) e00260, doi:10.1016/j.daach.2023.e00260.
[53] V. Parfenov, S. Igoshin, D. Masaylo, A. Orlov, D. Kuliashou, Use of 3D laser scanning and additive technologies for reconstruction of damaged and destroyed cultural heritage objects, Quantum Beam Sci. 6 (2022), doi:10.3390/qubs6010011.
[54] W.C. Shin, K.C. Wi, A study on ceramic restoration methods with full colour 3D printing (autotranslated), J. Conserv. Sci. 36 (2020) 306–314, doi:10.12654/JCS.2020.36.5.01.
[55] M. Torres-González, J.J. Martín-Del-Rio, F.J. Alejandre-Sánchez, M. León Muñoz, D. Bienvenido-Huertas, J.M. Macías Bernal, Guidelines for conservation and restoration of historic polychrome plasterwork: the church of St María la Blanca in Seville, Spain, Stud. Conserv. (2022), doi:10.1080/00393630.2022.2072096.
[56] A. Vazzana, O.A. Higgins, G. Oxilia, F. Lugli, S. Silvestrini, A. Nava, L. Bondioli, E. Bortolini, G. Di Domenico, F. Bernardini, C. Tuniz, L. Mancini, M. Bettuzzi, M.P. Morigi, M. Piperno, C. Collina, M. Romandini, S. Benazzi, High-accuracy methodology for the integrative restoration of archaeological teeth by using reverse engineering techniques and rapid prototyping, J. Archaeol. Sci. Rep. 44 (2022) 103511, doi:10.1016/j.jasrep.2022.103511.
[57] L. Conceição, S. Coentro, J. Teixeira, M. Vilargues, I. Coutinho, P. Urze, Loss compensation with porcelain fills : combining traditional techniques and emerging technologies, in: ICOM-CC Work. Gr. Glas. Ceram. Interim Meet. 9-11 Novemb. 2022, Lisbon, Port, 2022, pp. 237–242.
[58] R. De Vos, S. Bauvois, J. Verlinden, L. Acke, Application of 3D technology to create a detachable fill for an earthenware skyphos, Digit. Herit. Prog. Cult. Herit. Doc. Preserv. Prot. 9th Int. Conf. EuroMed, 2022 2022, 7-11 Novemb. 2022, Nicosia, CyprusTo Be Publ.
[59] F. Henriques, A. Bailão, J. Rocha, J. Costa, Restoration of an 18th century frame: 3D modelling, printing and matching color of decorative flowers elements, in: RECH5 - 5th Ed. Int. Meet. Retouching Cult. Heritage, 18-19 Oct 2019, 2020, pp. 313–322, doi:10.37558/gec.v18i1.854. Urbino, Italy.
[60] A. Oliveira, L. Ribeiro, N. Ferreira, The use of 3D scanning and printing in the restoration process of the exposed ceramic panels of Jorge Barradas (Palacio Da Justicia de Lisboa), in: RECH6 - 6th Int. Meet. Retouching Cult. Heritage, 4-6th November 2021, 2021, pp. 213–220.
[61] S. Peters, Gebruik van kunststeen voor de restauratie van het Antwerps Stationsgebouw, in: H. De Clercq, D. Van Gemert, R. van Hees (Eds.), WTA Stud. Aarschot, 9 Novemb, 2012 2012.
[62] J. Teixeira, Loss compensation using porcelain: a case study at vista Alegre porcelain factory, in: ICOM-CC Work. Gr. Glas. Ceram. Interim Meet. 9-11 Novemb. 2022, Lisbon, Port, 2022, pp. 47–55.
[63] 3D ArcheoLabRestoration and Reproduction in 3D Printing of Terracotta Statues, 3D ArcheoLab, 2021 https://www.3d-archeolab.it/portfolio-items/restauro-e-riproduzione-in-stampa-3d-di-statue-in-terracotta/?portfolioCats=461.
[64] Lincoln Conservation, Buxton Crescent, Lincoln Conserv, 2023, pp. 19–20 https://www.lincolnconservation.co.uk/projects/buxton-crescent/BUXTON accessed June 12, 2023.
[65] Lincoln ConservationSèvres Porcelain conservation, Lincoln Conserv, 2023 https://www.lincolnconservation.co.uk/projects/sevres-porcelain-conservation/SÈVRES accessed June 12, 2023.
[66] S. Van Oudheusden, D. Duggins, Conservation Treatment of ' View of the Sea at Scheveningen, Van Gogh Museum, 2019 Omroep Scheveningen https://www.youtube.com/watch?v=W7TJyONnY3U&t=1sConservation .
[67] A. Walen, J. Jooshesh, Dinosaur Skull Rises from a 3D Point cloud, Delta - Journalistisc Platf. TU Delft, 2020 https://www.delta.tudelft.nl/article/dinosaur-skull-rises-3d-point-cloud.