

UDK: 343.98 : 681.625.9

347.94 : 681.625.9

Review paper

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PRESERVING AND RECONSTRUCTING EVIDENCE WITH 3D PRINTING TECHNOLOGY: OPPORTUNITIES AND CHALLENGES

ABSTRACT

The application of 3D printing technology in forensic science has revolutionized evidence preservation and reconstruction. By creating accurate replicas of physical evidence, such as weapons, bones, or damaged objects, 3D printings safeguard the original items while enabling detailed visualization for courtroom presentations. This paper explores the key benefits of 3D printing in preserving evidence integrity, enhancing the understanding of complex cases, and supporting forensic education. It also addresses significant challenges, including the accuracy of 3D-printed models, legal admissibility, and ethical concerns related to evidence manipulation. The study concludes by emphasizing the need for standardized protocols and interdisciplinary collaboration to ensure the effective and reliable use of 3D printing in forensic investigations, ultimately contributing to more transparent and fair judicial processes.

Keywords: 3D printing technology, forensic sciences, evidence, courtroom

1. INTRODUCTION

Thanks in part to technological advances over the past decade, three dimensional (furthermore 3D) printing technologies have revolutionised industries such as healthcare, engineering and design. Its impact on forensic science is particularly notable, offering innovative methods that can contribute to evidence preservation, crime scene reconstruction and forensic demonstration. 3D printing is a form of additive manufacturing, which expresses the kind of construction where materials are placed on a building platform from scratch, as opposed to extractive, traditional manufacturing. There are three main technologies within additive manufacturing, which are stereolithography (furthermore SLA), selective laser sintering (furthermore SLS) and digital light processing (furthermore DLP). In SLS, we can

talk about selective binding technology, where we use powder (which can be metal or for example gypsum) as a binder or heat (in our case, a laser) to create a 3D printed object. Once printing starts, the first layer is fused onto a platform and layer after layer of thin powder layers are fused onto it until the model reaches its final state. The selective solidification technology involves the production of a solid model from a liquid, which requires selective energy to form. As with SLS, the first layer is placed on a solid platform, which is then moved around in the liquid to form the other layers. SLA, also known as stereolithography, is an example of the use of selective solidification technology, as it uses UV light to solidify the resin as a liquid using a laser or DLP.

Selective deposition, also known as layering, does not require a building platform, as mentioned above. Printing typically involves melting a filament and creating a new object from the molten plastic.¹

The selection of a particular technology for application depends on the characteristics of the object to be printed, its intended use, the available budget, and other factors. According to ISO/ASTM 52900, 3D printing has been classified into seven categories, and there are printers that are approved for medical purposes and applications. Due to the precision of modeling, 3D printing can be utilized in anatomical fields, as the printed models exhibit a deviation of less than 1 mm or 3% from the actual objects.²

Nowadays, we are capable of printing concrete structures, and even producing human organs, pharmaceuticals, and food products. Since the appearance of the first commercially available printers in 1989, it can be stated that technological advancement and the widespread use of printers among a broader range of users have continuously posed challenges for representatives of scientific fields, the market, and law enforcement authorities.³

Accurate replicas created from digital models are suitable for duplicating fragile or perishable evidence and can thus be used, for example, to print replicas of skeletal remains. The initial forensic applications of 3D printing can be traced back

¹ Horvath, J., A Brief History of 3D Printing, in: *Mastering 3D Printing*, Apress, Berkeley, CA, 2014, pp. 3–10. DOI: https://doi.org/10.1007/978-1-4842-0025-4_1.

² Carew, R.M.; Errickson, D., *An Overview of 3D Printing in Forensic Science: The Tangible Third-Dimension*, *Journal of Forensic Sciences*, 65, 2020, pp. 1752–1760.

³ Horváth, O.; Maróti, P., *3D nyomtatott fegyverek: Vélt vagy valós veszélyek?*, in: Gaál, G.; Hautzinger, Z. (eds.), *A XXI. század biztonsági kihívásai*, Magyar Hadtudományi Társaság Határőr Szakosztály Pécsi Szakcsoport, 2018, pp. 73–78.

to reconstruction procedures aimed at anthropological and pathological identification and trauma analysis.⁴

The emerging forensic fields incorporate the expertise of various scientific disciplines in order to effectively address legal questions. Accordingly, 3D forensic science (3DFS) integrates the methods of forensic radiography, medicine, anthropology, and photography in support of investigations, building upon the knowledge of digital forensic science. Among the objectives of 3DFS is the creation of visual aids that assist both the court and the jury in interpreting the evidence. Injury mechanisms, as well as crime scene photography using 3D printing or imaging techniques, are all considered part of the field of 3D forensic science.⁵

Pham and colleagues⁶ also noted in their 2021 article that post-mortem computed tomography (PMCT) can be applied, among other uses, for age estimation through the accurate 3D visualization of dentition, as well as for overcoming limitations such as rigor mortis and other visualization challenges encountered during autopsy. In addition to dental analysis, the inclusion of the mandible in 3D modeling contributes to the process of personal identification, enabling more accurate estimations of sex and age. However, it is important to highlight that dimensional discrepancies can be observed between the original dentition and mandible and their 3D replicas, which must be considered limitations, even if such differences are minimal.

In addition to dentition, the skull, face, and other body parts can also be printed following scanning, thereby enabling personal identification as well. In connection with dental analysis, bite mark examination can also be mentioned, involving the comparison of bite marks found at crime scenes with the dentition of suspects. With the help of 3D printing, tool marks can also be matched to injury marks. The identification of footwear impressions is likewise supported by scanning, which provides additional information (such as depth dimension), and the impressions can be printed and preserved. From individual digital models, scaled-up replicas

⁴ Simon, G.; Tóth, D.; Heckmann, V. et al., *Application of 3D printing in assessment and demonstration of stab injuries*, International Journal of Legal Medicine, 136 (2022), pp. 1431–1442. DOI: <https://doi.org/10.1007/s00414-022-02846-6>.

⁵ Baier, W.; Warnett, J.M.; Payne, M.; Williams, M.A., *Introducing 3D printed models as demonstrative evidence at criminal trials*, Journal of Forensic Sciences, 63(4), 2017, pp. 1230–1237. DOI: <https://doi.org/10.1111/1556-4029.13700>.

⁶ Pham, C.V.; Lee, S.-J.; Kim, S.-Y.; Lee, S.; Kim, S.-H.; Kim, H.-S., *Age estimation based on 3D post-mortem computed tomography images of mandible and femur using convolutional neural networks*, PLOS ONE, 16(5), 2021, e0251388. DOI: <https://doi.org/10.1371/journal.pone.0251388>.

can also be produced if they serve the purpose of enhancing understanding and visualization.⁷

Laser scanning supports the reconstruction of crime scenes by enabling the creation of scaled-down models of specific locations, which can be presented in court. This technique allows not only for the depiction of accident scenes but also for the visualization of multiple scenarios or versions of criminal events, thereby facilitating the uncovering of past occurrences.⁸

As previously mentioned, 3D printing and imaging technologies can also be applied in the field of forensic ballistics. On the one hand, the reconstruction of bullet trajectories can be performed both at the crime scene and within the human body using laser scanning or post-mortem computed tomography (PMCT). In addition to virtual trajectory reconstructions, the analysis of bloodstain patterns is also supported by these innovative technologies, thereby opening new dimensions in uncovering past events.⁹

The diversity of the aforementioned forensic fields also highlights one of the primary reasons for applying 3D printing: the preservation of evidence. Evidence may be fragile, perishable, or only partially accessible. Environmental factors, the natural decomposition of the human body, and potential damage during transport or storage all raise questions and influence the possibilities of using such materials as admissible evidence. Traditional methods, such as photographs (2D) or sketches, are incapable of capturing the full spectrum of the scene or recording three-dimensional information. This limitation in representation affects not only the crime scene itself but also the subsequent stages of the justice process, including the courtroom, where understanding spatial relationships and complex details is equally crucial. By applying 3D models, the interpretative framework of jurors, judges, prosecutors, legal professionals, and laypersons is expanded, enabling more comprehensible legal reasoning and more accurate interpretation.¹⁰ According to an investigative analysis published in *The Guardian*, between September 2021 and September 2022 in England and Wales, 7,316 cases were reported in which proceedings did not reach the trial stage due to lost or destroyed evidence. These cases included 16 homicides and over a hundred sexual offenses.

⁷ Vanisree, C.R.; Nagesh, D.; Gowtham Sai, P., *Advances in Forensic Science: Integration of 3D Imaging and 3D Printing*, Journal of Emerging Technologies and Innovative Research, 10(12), 2023, pp. 395–404.

⁸ Sheshtar, F.M.; Alhatlani, W.M.; Moulden, M.; Kim, J.H., *Comparative analysis of LiDAR and photogrammetry for 3D crime scene reconstruction*, Applied Sciences, 15(3), 2025, p. 1085. DOI: <https://doi.org/10.3390/app15031085>.

⁹ Carew, R.M.; Errickson, D., *op. cit.* note 2, p. 1754–56.

¹⁰ Baier et al., *op. cit.* note 5, p. 1230–1237.

As experts cited in the report emphasize, the most critical issue regarding these cases is not merely the inability to solve a cold case or to appeal a previous decision, but rather the loss of the legal procedure itself. The 2023 Casey Report also documented that evidence storage conditions were inadequate, referencing broken and outdated refrigerators, and even an incident where a heatwave caused one of the refrigerators to fail, leading to the destruction of the evidence and the collapse of the associated cases.¹¹

A previous article examined the period between October 2018 and August 2021, during which legal proceedings were discontinued in a total of 20,838 cases due to lost or destroyed evidence.¹² A simple calculation shows that the number of cases recorded between 2022 and 2023 exceeds the average of the preceding three years.

At the same time, the importance of evidence preservation can also be approached from the perspective of the defense, for example, when such evidence forms the basis of a motion to suspend proceedings. Based on the above, the aim of this study is to explore the potential applications of 3D printing technologies in the preservation, reconstruction, and presentation of evidence. The study seeks answers to the following questions:

- To what extent is 3D printing technology capable of accurately reproducing evidence for future legal use?
- Are 3D replicas capable of improving the understanding and reliability of evidence for participants in criminal proceedings?
- Are there any potential disadvantages or limitations to the application of 3D printing technologies in forensic sciences?

Based on these questions, the following hypotheses can be formulated:

H1: 3D printing enhances the preservation of evidence, as it produces accurate and durable physical copies of fragile or perishable items, which are also easy to transport.

¹¹ Devlin, H., *Missing evidence led to 16 homicides in England and Wales not going to trial*, The Guardian, 3 September 2023, <https://www.theguardian.com/uk-news/2023/sep/03/lost-missing-evidence-cases-freedom-of-information-police> (downloaded: 28 February 2025).

¹² Morton's Solicitors, *Police often lose vital evidence – new research reveals*, 15 October 2023, <https://www.mortons-solicitors.co.uk/police-often-lose-vital-evidence-new-research-reveals/> (downloaded: 28 February 2025) and Martinsp, S., *Lost and Destroyed Evidence: The Search for a Principled Approach to Abuse of Process*, The International Journal of Evidence & Proof, 9(3), 2005, pp. 158–182. DOI: <https://doi.org/10.1350/ijep.2005.9.3.158>.

H2: The use of 3D replicas in the courtroom improves the comprehension of evidence by actors in criminal proceedings.

H3: Despite its advantages, the application of 3D printing technologies presents challenges related to ethical concerns and accessibility.

To address these questions and test the hypotheses, a literature-based analysis was conducted.

The relevance of this research lies in the fact that the application of 3D printing technologies and models enables the re-examination of critical evidence, ensuring its long-term availability and allowing for its analysis in protracted cases or during appeals. Beyond supporting investigations, such informative evidence provides additional interpretative dimensions for participants in the justice system. In the future, AI-based models may be capable of automatically detecting correlations between individual pieces of evidence, thereby contributing to faster and more accurate investigations, fairer procedures, more reliable justice, and ultimately, better outcomes. With the on-site use of handheld scanners, evidence can be rapidly and reliably replicated in a digitally storable and analyzable format, from which physical replicas may later be produced. The development of a global standard for the admissibility of 3D-printed evidence is also expected in the near future.

2. FORENSIC APPLICATIONS OF 3D PRINTING

2.1. Printing of evidence

The application of 3D technologies in the forensic field extends to the duplication of physical evidence and the creation of replicas. These unrestricted reproductions, accessible to experts,¹³ support the execution of identification procedures and the understanding of evidence and past events through demonstrations. Replicas do not merely represent the reproduction of simple objects but may also include the printing of weapons left at a crime scene,¹⁴ which can then be examined freely without compromising the integrity of the original evidence. In addition to weapons, damaged or fragmented objects can also be printed after scanning, thanks to additive manufacturing technology.

One of the first scientifically documented cases involving the use of 3D printed models as evidence in criminal proceedings is linked to a homicide trial in the United Kingdom, the details of which were published by Baier and colleagues in

¹³ Carew, R. M.; Errickson, D., *op. cit.* note 2, p. 1754-56.

¹⁴ Horváth, O.; Maróti, P., *op. cit.* note 3, p. 75.

2017. In the case, two men were accused of beating a victim who later died in the hospital due to cranial injuries. A claw hammer and a wrench were found during the search of the crime scene. As the two defendants blamed each other, the central questions were who actually committed the act - if not both of them - and which weapon had been used.

During the proceedings, images were captured of a portion of the skull using micro-CT to visualize the sustained injuries and analyze the fracture patterns. The micro-CT data were processed to produce a full-scale 3D print using the SLA method. The investigation revealed two distinct fracture patterns: one was elongated and narrow, while the other had a square shape with rounded corners. Based on this, it was concluded that either two different weapons had been used or that the injuries occurred at different times, thereby resulting in collision surfaces with differing geometries.

The case is particularly significant as it was the first to examine the admissibility of 3D replicas in court. Criminal Procedure Rule (CrimPR) 19 sets the admissibility criteria for expert evidence, and in this case, the Harston Rules - governing demonstrative evidence - also had to be considered.¹⁵

A previous study¹⁶ had established that 3D replicas can adequately represent anatomical features, even if they are not perfectly accurate. However, the technology continues to evolve. In this case, careful consideration was given to the material used to create the replica to ensure it would be deemed admissible by the judge. The model was created to resemble the original skull as closely as possible. To minimize the possibility of eliciting emotional responses, only the relevant portion of the skull was printed. During the trial, the forensic pathologist was able to present their expert opinion to the jury using the printed replica.

Although several studies have addressed jurors' competencies regarding medical or scientific evidence, the paper emphasizes that visual and tactile evidence significantly enhances comprehension and that active engagement improves memory retention. In the case presented, the defendants were found guilty. The role of the 3D prints clearly lay in enhancing the understanding of the evidence.¹⁷ In a case predating the first scientifically documented example, a man was sentenced to life imprisonment for fatally stabbing former Plymouth Argyle

¹⁵ Baier et al., *op. cit.* note 5, p. 1230-1237.

¹⁶ Silva, D.N.; de Oliveira, M.G.; Meurer, E.; Meurer, M.I.; da Silva, J.V.L.; Santa-Bárbara, A., *Dimensional error in selective laser sintering and 3D-printing of models for craniomaxillary anatomy reconstruction*, Journal of Cranio-Maxillofacial Surgery, 36(8), 2008, pp. 443–449. DOI: <https://doi.org/10.1016/j.jcms.2008.07.003>.

¹⁷ Baier et al., *op. cit.* note 5, p. 1230-1237.

footballer Alex Peguero Sosa in the neck with a broken glass bottle in 2014. In the proceedings, the weapon used in the attack was 3D printed, and the prosecution asked the defendant to demonstrate how he had assaulted the victim. The production of the replica took 28 hours, and its use allowed for the safe reconstruction of past events.¹⁸

2.2. Crime Scene Reconstruction

The application of 3D technologies plays a prominent role in the reconstruction of crime scenes,¹⁹ as they are capable of providing accurate and detailed models for the reconstruction of past events and for later examinations. By revealing the spatial complexity of a scene, such technologies can eliminate - or at least mitigate - the limitations associated with 2D photographic images or sketches. Another major advantage of three-dimensional scene reconstruction is the ability to preserve critical evidence, as well as to document the condition of the scene regardless of environmental or human factors. In cases where legal proceedings extend over several years, it becomes particularly important that the recordings captured at the time of the scene inspection can be revisited virtually.²⁰

When discussing crime scene reconstruction, it is important to distinguish between 3D scanning and 3D printing. The former ensures the digital documentation of the scene, enabling the verification and elimination of different scenario versions. In contrast, 3D printing - as noted in the previous section - involves the creation of physical objects derived from digital data. These replicas contribute to improved understanding and the making of more well-founded decisions.²¹ The combination of the two processes can also enhance analysis, interpretation, and ultimately, judgment.

¹⁸ BBC News, *Plymouth Argyle youth player murder trial used 3D-printed bottle*, 20 April 2015, <https://www.bbc.com/news/uk-england-devon-32385554> (downloaded: 1 March 2025).

¹⁹ Carew, R.M.; Errickson, D., *op. cit.* note 2, p. 1752-1760.

²⁰ Abdelaal, O.; Aldahash, S.A., *Realization of impression evidence with reverse engineering and additive manufacturing*, Applied Sciences, 14(13), 2024, p. 5444. DOI: <https://doi.org/10.3390/app14135444>.

²¹ Villa, C.; Lynnerup, N.; Jacobsen, C., *A virtual, 3D multimodal approach to victim and crime scene reconstruction*, Diagnostics, 13(17), 2023, p. 2764. DOI: <https://doi.org/10.3390/diagnostics13172764>.

In scene modeling, both LiDAR (Light Detection and Ranging) laser scanning and photogrammetry technologies must be highlighted. Esposito and colleagues²² conducted investigations at more than 200 crime scenes and concluded that the use of laser scanning (LS) technology significantly improved the ability to depict scenes in a detailed and accurate manner. Between January 2019 and June 2022, five cases from their study were specifically highlighted, each demonstrating the effectiveness of LS technology in contributing to investigations through the creation of detailed scene diagrams. Among other outcomes, these diagrams allowed investigators to clarify a case by verifying investigative scenarios, where the distinction between suicide and intentional homicide needed to be established. Naturally, 3D models in the form of animated videos can also be created for the reconstruction of individual crimes. In a well-known case reported by, among others, the BBC, such 3D modeling was used in the murder committed by South African Paralympic athlete Oscar Pistorius. Reeve Steenkamp, the model, had been dating Pistorius for three months when, on the early morning of February 14, 2013, he shot and killed her. In his testimony, Pistorius admitted to shooting his girlfriend while she was in the bathroom, claiming he believed an intruder had entered the house.

He stated that he had already been in bed without his prosthetic legs while his girlfriend was doing yoga exercises. In the early hours, he woke up, stepped onto the balcony to get some fresh air and bring in the fan. Upon returning to the dark room, he heard a noise from the bathroom, retrieved his gun from under the bed, and approached the area without his prostheses. He did not turn on the light. Shouting for the intruder to leave, he fired shots at the toilet door, then told his girlfriend to call the police - still without turning on the light. When he returned to the bed and realized she wasn't there, he went to the toilet, broke down the door, and found his girlfriend still alive over the toilet. She later died from her injuries. In the first-instance trial, he was sentenced to five years in prison - not for murder, but for culpable homicide. In 2014, the prosecution filed an appeal, arguing that the act was intentional. In 2015, the Supreme Court of Appeal found Pistorius guilty of murder and sentenced him to imprisonment. He was conditionally released in January 2024.

The resolution of the case heavily relied on verifying the different scenarios - what the accused could have seen and how, and whether, based on the shooting angles, he had indeed fired the weapon without his prosthetic legs, thus supporting his claim of vulnerability and fear. Thanks to the model, the court was able to

²² Esposito, M.; Sessa, F.; Cocimano, G.; Zuccarello, P.; Roccuzzo, S.; Salerno, M., *Advances in Technologies in Crime Scene Investigation*, Diagnostics, 13(20), 2023, p. 3169. DOI: <https://doi.org/10.3390/diagnostics13203169>.

understand the scene more accurately and better interpret the events, allowing for the exclusion of certain scenarios (in this case, the defendant's claim), which ultimately affected the outcome of the case.²³

The identified cases have demonstrated that the use of visualization techniques, including the application of 3D models, plays a prominent role in forensic investigations and criminal proceedings. However, imaging technologies are rapidly advancing, and it is therefore necessary to briefly address the use of immersive technologies in criminal procedure. The use of virtual reality (VR), particularly through photogrammetric applications, allows for the examination and analysis of crime scenes, the improvement of documentation processes, and the training of law enforcement personnel. Through VR, experts can conduct analyses that reduce the risk of contamination and expert bias, while also enabling assessments in particularly hazardous situations (e.g., the presence of dangerous chemicals). Deep learning algorithms further allow for the automatic detection of objects. In their 2024 publication, Zappalà and colleagues²⁴ demonstrated the effectiveness of combining photogrammetry, VR, and deep learning algorithms at a simulated crime scene, successfully identifying objects with potential evidentiary value. VR headsets can support not only experts but also offer jurors the opportunity to virtually explore crime scenes.

The use of HoloLens technology can further enhance the effectiveness of crime scene inspections, drawing attention to the potential of both augmented reality (AR) and VR. The technology helps overcome temporal and geographic constraints between investigative teams.²⁵

The application of these technologies clearly indicates that the future will focus on the integration of various methods and the utilization of their combined advantages. Nonetheless, it is equally important to emphasize the need to educate both practicing professionals and students about these new technologies.

This is supported by a 2022 study conducted in India. The results showed that the use of 3D scanning and 3D printing in forensic practice is still relatively new among forensic medical experts. Among the respondents - 54 experts and 10

²³ BBC News, *Oscar Pistorius trial: Evidence*, 16 April 2014, <https://www.bbc.com/news/world-africa-26417240> (downloaded: 26 February 2025).

²⁴ Zappalà, A.; Guarnera, L.; Rinaldi, V.; Livatino, S.; Battiato, S., *Enhancing crime scene investigations through virtual reality and deep learning techniques*, arXiv preprint, 2024. DOI: <https://doi.org/10.48550/arXiv.2409.18458>.

²⁵ Albeedan, M.; Kolivand, H.; Hammady, R., *Effect of Augmented Reality and Virtual Reality in Crime Scene Investigations*, in: Proceedings of the 16th International Conference on Developments in eSystems Engineering (DeSE), Istanbul, Türkiye, 2023, pp. 653–657. DOI: <https://doi.org/10.1109/DeSE60595.2023.10469037>

scientific officers - those working in central laboratories were familiar with the technology and were applying it in practice. Based on the findings, the authors highlighted the importance of education and the transfer of new knowledge.²⁶

3. ADVANTAGES AND OPPORTUNITIES, CHALLENGES AND LIMITATIONS

The application of 3D printing and scanning technologies offers numerous advantages during criminal proceedings. By enabling the creation of accurate replicas of evidence, these technologies support analysis, demonstration, and the understanding of both scientific and legal contexts. Based on the studies discussed above, it can be concluded that depending on material selection and printer type, the resulting replicas may vary in precision, yet they are suitable for forensic examinations and legal use.²⁷ Integrating 3D printing with 3D scanning further enhances these benefits.

One key aspect that must be highlighted is the accuracy and level of detail in the models²⁸. Unlike traditional methods - such as the use of plaster casting - 3D replicas can offer greater detail, thereby supporting identification and expert analysis. For detailed examination, high reconstruction accuracy is essential, which can be achieved, for example, through structured light scanning.²⁹ 3D printing can also be particularly useful in cases that require the reconstruction of certain pieces of evidence - for instance, reassembling skull fragments based on CT images.³⁰

Replicas allow for the protection of original evidence and ensure its integrity. This is particularly significant in cases involving perishable or degradable evidence - such as bone fragments or evidence contaminated with genetic material. Printed models can be stored long-term, enabling examinations to be conducted months or even years later.

²⁶ Johnson, A.; Jani, G.; Pandey, A., *Application of 3D scanning and 3D printing in forensic practices: A preliminary survey among forensic practitioners in India*, Forensic Imaging, 28 (2022), p. 200498. DOI: <https://doi.org/10.1016/j.fri.2021.200498>.

²⁷ Baier et al., *op. cit.* note 5, p 1230-1237.

²⁸ Kluska, E.; Gruda, P.; Majca-Nowak, N., *The accuracy and the printing resolution comparison of different 3D printing technologies*, Transactions of the Institute of Aviation, 3(252), 2018, pp. 69–86. DOI: <https://doi.org/10.2478/tar-2018-0023>.

²⁹ Abdelaal, O.; Aldahash, S.A., *op. cit.* note 20, p. 5444.

³⁰ Jakobsen, S.R.; Pedersen, C.C.; Thomsen, A.H.; Hansen, K., *3D-print as a template for reassembly of skull fragments in a homicide case*, Annals of 3D Printed Medicine, 12 (2023), p. 100137. DOI: <https://doi.org/10.1016/j.stlm.2023.100137>.

Forensic radiology, through the use of rapid prototyping (RP), allows for the creation of 3D skull models using computed tomography. When using the selective laser sintering (SLS) method, these models uphold medical ethics, including respect for the dignity of the deceased, while facilitating the presentation of trauma analysis.³¹ In the aforementioned English murder case, it was also emphasized that biological tissues may pose health risks and that examination or demonstrative use of the original skull could cause damage. Finally, it is important to highlight the emotional and moral impact of such procedures - not only on those involved in the trial but also on the relatives of the deceased. By using replicas, both health and evidentiary risks can be avoided, and additional copies can be produced as needed. Expert testimonies can be more easily understood when judges and other participants are able to physically handle the objects and better grasp the mechanisms of injury and their three-dimensional relationships. The previously mentioned moral and ethical concerns regarding the use of biological remains are also mitigated by the use of 3D-printed replicas.³² By creating digital models of crime scenes, past events can be reconstructed, and alternative scenarios visualized - making causal relationships and event sequences verifiable and comprehensible. The authors also emphasized that integrating innovation is essential for investigators and prosecutors.³³ In addition to investigators and prosecutors, judges gain new interpretive perspectives through these models, and jurors should not be overlooked either.

According to the study by Bright and Goodman-Delahunty (2006)³⁴, while verbal evidence - such as witness testimony describing the circumstances of a murder - does not elicit strong emotional reactions from jurors, photographic depictions of such events trigger a significantly more intense emotional response, including feelings of anger. The conviction rate was notably higher among jurors when photographic evidence was presented than when it was not. The detailed physical representation of a victim's injuries - whether through original images or 3D replicas - can therefore introduce potential bias among jurors, making the defendant appear in a more unfavorable light. In each case, it is thus essential to carefully assess whether the use of replicas poses a risk, as this may result in a ruling of inadmissibility. Consequently, English lawyers may be reluctant to

³¹ Kettner, M.; Schmidt, P.; Potente, S.; Ramsthaler, F.; Schrodtt, M., *Reverse engineering—Rapid prototyping of the skull in forensic trauma analysis*, Journal of Forensic Sciences, 56(4), 2011, pp. 1015–1017. DOI: <https://doi.org/10.1111/j.1556-4029.2011.01769.x>.

³² Baier et al., *op. cit.* note 5, p. 1230-1237.

³³ Dufeniuk, O.; Melnyk, N.; Nahorniak, Yu.; Melnyk, S., *Innovative potential of 3D technologies in crime investigation*, Social and Legal Studies, 7(4), 2024, pp. 222–230. DOI: <https://doi.org/10.32518/sals4.2024.222>.

³⁴ Bright, D.A.; Goodman-Delahunty, J., *Gruesome Evidence and Emotion: Anger, Blame, and Jury Decision-Making*, Law and Human Behavior, 30(2), 2006, pp. 183–202. DOI: <https://doi.org/10.1007/s10979-006-9027-y>.

employ them in court proceedings.³⁵ When it comes to medical and scientific matters, it is particularly important that jurors understand the facts and expert opinions arising in relation to the crime. The use of replicas allows for the comprehension of complex processes, such as the analysis of bloodstain patterns.³⁶ Considering the financial and resource-related aspects, 3D printing enables the rapid production of prototypes and replicas of evidence without requiring highly expensive materials. While the use of specialized software does involve initial investment costs, these are offset over time -especially when the technology is employed for educational purposes.

The application of 3D printing technologies offers numerous advantages in the fields of investigation, evidence presentation, and courtroom proceedings. However, it is essential to also consider the potential challenges and limitations associated with their use. The accuracy of printed models depends not only on the equipment employed but also significantly on the quality of the input data.³⁷ (Formslab).

The forensic use of printed evidence remains an evolving field, meaning its legal admissibility and courtroom practices are still in development. Consequently, it is necessary to assess compliance with standards and establish procedural protocols for their application.

While we highlighted the precision of 3D models as a benefit, under limitations it is important to mention the potential distortions in microscopic details that can occur during the printing process, as shown in experiments involving various printing technologies.³⁸

The regulation of printed evidence is not standardized worldwide. During the literature review, we found that documented cases primarily originate from Anglo-American legal systems. The judicial consideration of models used for demonstrative purposes is not yet universally accepted, nor are the criteria governing their admissibility clearly defined across all jurisdictions.

³⁵ Baier et al., *op. cit.* note 5, p. 1230-1237.

³⁶ Home, P.H.; Norman, D.G.; Wade, K.; Spearing, E.; Williams, M.A., *3D scanning a crime scene to enhance juror understanding of bloodstain pattern analysis evidence*, Science & Justice, 64(3), 2024, pp. 333–338. DOI: <https://doi.org/10.1016/j.scijus.2024.04.007>.

³⁷ Formlabs, *Guide to 3D printing materials: Types, applications, and properties*, n.d., <https://formlabs.com/en/blog/3d-printing-materials/> (downloaded: 27 February 2025).

³⁸ Loc. cit.

From a budgetary perspective, it is evident that the cost of high-precision scanners and printers used in forensic contexts can be substantial - investments that smaller institutions and educational facilities may be unable to afford. Additionally, some authors emphasize that the application of 3D printing is not always cost-effective and should be viewed more as a supplementary rather than a replacement method in forensic medical examinations.³⁹

Lastly, we must not overlook the ethical and data protection concerns. 3D printers are capable of producing weapons and explosives, among other items. As with other types of evidence, the possibility of manipulation arises, which underscores the importance of securely storing and encrypting digital files.⁴⁰

The summary of advantages, disadvantages, challenges, and opportunities clearly illustrates that numerous aspects of the application of 3D printing and related technologies are still in a developmental phase. Ongoing research, the collection of case studies, and the elaboration of legal regulations and procedural protocols all contribute to the transformation of this indispensable technology into a key tool within justice processes.

In summary, this chapter presented the main advantages, potential applications, and practical challenges associated with the implementation of 3D technology in forensic science and criminal procedure. Although it briefly touched upon certain legal concerns - such as the risk of jury bias, the lack of standardized protocols, and the potential for manipulation - these issues warrant more in-depth legal analysis. Accordingly, the following chapter will focus specifically on the legal implications of employing 3D technologies as evidence in criminal proceedings, with particular attention to their classification, admissibility, and the impact on the guarantees of a fair trial.

4. LEGAL ASPECTS OF USING 3D TECHNOLOGY AS EVIDENCE IN CRIMINAL PROCEDURE

Criminal justice systems are increasingly incorporating digital and visualization technologies, including 3D modeling and printing. These tools have gained particular prominence in the areas of crime scene reconstruction and the demonstration of bodily injuries, as they are capable of conveying information in

³⁹ Simon et al., *op. cit.* note 4, p. 1431-1442.

⁴⁰ Henningsen, M.J.; Thorlacius-Ussing, L.; Jensen, L.G. et al., *3D printed skulls in court – a benefit to stakeholders?*, International Journal of Legal Medicine, 137 (2023), pp. 1865–1873. DOI: <https://doi.org/10.1007/s00414-023-03054-6>.

a vivid and detailed manner to judges, jurors, and other procedural actors - as illustrated in the previous chapter through several examples.⁴¹ However, 3D models are not merely technical aids; they are evidentiary tools with legal relevance, whose use raises numerous procedural and evidentiary questions.

In relation to the use of this technology, one of the key issues is how 3D tools fit into the legal system of evidence: should they be regarded as demonstrative aids or as expert evidence? Furthermore, what admissibility requirements must they meet, and what impact might they have on procedural fairness - such as impartial judicial decision-making or the exercise of the right to defense? These questions are particularly timely given the current absence of uniform, codified procedural standards for handling 3D technology-based evidence.

The use of technology raises the question of how 3D tools are to be integrated into the legal system of evidence: should they be regarded as demonstrative aids or interpreted as expert evidence? Furthermore, what criteria must they meet in terms of admissibility, and how might they affect the fairness of the proceedings - for example, the impartiality of judicial decision-making or the enforcement of the right to defense? These questions are particularly timely, given the current absence of uniform, codified procedural standards for handling evidence produced with 3D technology.

The aim of this chapter is to review the main legal aspects of the application of 3D technology in criminal proceedings, with particular focus on its interpretation as evidence, the criteria for admissibility, and its impact on the requirements of a fair trial.

Before evaluating the use of 3D-related files and tools as evidence, it is necessary to briefly address the nature of the Hungarian evidentiary system. In Hungarian criminal procedure, there is scholarly debate regarding whether the principle of free evaluation of evidence applies in an unrestricted form. According to the currently effective Criminal Procedure Act (Act XC of 2017 on Criminal Procedure; hereinafter: CPA), several sources consider the free evaluation of evidence to be the prevailing model. However, other authors - such as Flórián Tremmel in his commentary - refer to the concept of a “not entirely free evidentiary system”.⁴² According to this view, although in principle all evidentiary means defined by the CPA may be used, the law may still prescribe specific methods for applying certain evidentiary instruments or conducting certain

⁴¹ Baier et. al., *op. cit.* note 5, p. 1230-1237.

⁴² Tremmel, F., *Bizonyítékok a büntetőeljárásban*, Dialóg Campus Kiadó, Budapest-Pécs, 2006.

evidentiary procedures. Section 167 (1) of the CPA states that “in criminal proceedings, any means of evidence defined by law may be freely used, and any evidentiary procedure may be freely conducted,” yet the law may also mandate the use of certain evidentiary means. These include witness testimony, the accused’s statement, expert opinion, probation officer’s report, physical evidence (including documents and records), and electronic data (CPA Section 165).

Proof is an activity aimed at the past, with the objective of uncovering legally relevant facts.⁴³ Establishing these facts forms the basis for proper legal qualification, which may lead either to sentencing or the acquittal of the defendant. According to the principle of *in dubio pro reo* - which prevails in Hungarian law - facts that are not proven beyond reasonable doubt may not be interpreted to the detriment of the accused (the presumption of innocence). Accordingly, proof is a legally regulated activity, which may only be conducted by persons and authorities authorized by law, in compliance with procedural rules, rights, and obligations. Taking all of the above into account, only such information may be used in the evidentiary process whose source, acquisition, recording, and processing meet the procedural requirements, fulfill the criterion of authenticity, and whose truthfulness can be properly substantiated.

Verification of the authenticity and reliability of data collected during the investigation is ultimately the essence of proof. The issue of reliability is closely linked to the question of the manipulability of digital data and evidence,⁴⁴ especially in the present context, where captured recordings (generated via photogrammetry or laser scanning) or printable files qualify as electronic data. Member States impose specific requirements on the collection and evaluation of e-evidence to ensure its admissibility in court proceedings.⁴⁵

The current Hungarian Code of Criminal Procedure does not explicitly categorize "digital evidence" as a separate type; however, it includes electronic data and information systems within the broader category of traditional evidence. (It is worth noting that, both in Hungarian and international legal literature, the terms digital and electronic data or evidence are often used interchangeably.)

Electronic data can be accessed both in virtual space and in physical form, for example, through mobile phones or computers.⁴⁶ This study does not intend to

⁴³ Fantoly, Zs.; Gácsi, E.A., *Eljárási büntetőjog – Statikus rész*, Iurisperitus, Szeged, 2013, p. 202.

⁴⁴ Gyaraki, R., *A számítógépes bűnözés nyomozásának problémái*, Doktori disszertáció, Pécsi Tudományegyetem Állam- és Jogtudományi Doktori Iskola, Pécs, 2019.

⁴⁵ Loc. cit.

⁴⁶ Loc. cit.

address the issue of physical evidence in relation to 3D technologies - such as the topic of printed weapons - where the digital footprint or the file of the tool used in the commission of a crime serves as evidence during the investigation.

Accordingly, it can be stated that the classification of models created using 3D technology is not unambiguous, as they may fulfill multiple evidentiary functions. In certain cases, they serve as demonstrative evidence - that is, they visualize known data or facts for the court to enhance understanding. In other cases, however, the model may function as an independent expert result, especially when scientific methodology such as forensic reconstruction is applied during its creation.⁴⁷

Demonstrative tools generally do not prove new facts but illustrate existing claims - for example, by depicting the crime scene, the trajectory of a gunshot, or the location of an injury. Digital demonstrative tools are computer-aided graphics capable of summarizing hours of witness testimony, simplifying complex concepts, and highlighting weaknesses in the opponent's argumentation.⁴⁸

In addition to demonstrative evidence, it is also necessary to examine cases in which, through the "intervention" of an expert, new evidence emerges as a result of 3D technology that was previously unknown. Expert opinions - especially those provided by forensic medical experts - constitute a specific and complex form of evidence in criminal proceedings, combining both personal (expert) and physical (linked to the object of examination) characteristics. According to judicial practice, an expert opinion is admissible only if it is justified, truthful, clear, and objective.⁴⁹ The core of assessing an expert opinion lies in its probative value, which is based on the expert's competence and the credibility of the applied methods.

Expert opinions can be classified as definitive, probabilistic, or indeterminate. The type of opinion depends on the nature of the fact being proven and the quality of the available materials for analysis. The court cannot accept an expert opinion without reservation if it does not meet the statutory requirements - for instance, if it contains contradictions or lacks clarity. In such cases, the court must request clarification or supplementation from the expert, or appoint a new expert. If there

⁴⁷ Baier et al., *op. cit.* note 5, p. 1230-1237.

⁴⁸ Keller, J.L.; Scolnick, C.A., *Demonstrative Evidence: Tell and Show*, *Litigation*, 47(3), 2021, pp. 43-48. URL: <https://www.jstor.org/stable/27191906>.

⁴⁹ Barta, E.; Nagy, J., *Az igazságügyi orvosszakértőkről*, Rendőrtiszt Főiskola, Budapest, 2001.

are conflicting expert opinions, they must be heard together in court to allow for direct comparison and clarification.⁵⁰

The theory of expert opinion admissibility has its roots in the U.S. justice system, dating back to the 1923 *Frye v. United States* case. The Frye test requires that expert opinions, in addition to being relevant, must also be generally accepted within the professional community. The purpose of the test was to prevent courts from being influenced by theories and methods that, despite their innovation, lacked proven credibility.⁵¹

Taking all of this into account, it can be concluded that professional reconstructions created using 3D technology can be considered expert opinions in criminal proceedings, provided that their objective evaluation is ensured during the process and they meet the content requirements for expert reports. For example, a 3D model created based on a forensic medical report may contain new information - such as the direction and position of penetration angles related to the victim's injuries - that can serve to confirm or rule out certain scenarios during reconstruction.

In summary, it can be stated that digitally created or printed models may fall into multiple categories of evidence depending on their context and the manner of their creation. Currently, in Hungary, there is no specific provision in the Code of Criminal Procedure regarding the use of 3D technology; therefore, the handling of such tools is subject to case-by-case consideration. (It should be noted, however, that 3D site models are typically used in high-profile crimes - mostly homicides - based on images recorded during the crime scene investigation using photogrammetry or laser scanning.) Whether we are dealing with an expert opinion or a demonstrative tool, in both cases, the model's method of production, data source, and processing must be credible and comply with the requirement of objectivity.

While Section 197 of the Code of Criminal Procedure stipulates the conditions under which an expert opinion may not be accepted - including lack of clarity - the 2016 Act XXIX on Judicial Experts, Section 47, outlines the mandatory content elements of expert reports, such as findings, a brief description of the examination method, professional determinations, and the expert's opinion. In such cases, the method of modeling may be included as part of the method description. As for the Frye test, it is evident even from the technical and

⁵⁰ Szilvássy, Z., *Az (orvos)szakértői bizonyítás a büntetőeljárásban*, Debreceni Jogi Műhely, 2023/3–4., pp. 95–113. URL: <https://szakcikkkadatbazis.hu/doc/6309400>.

⁵¹ Hoge, S.K.; Grisso, T., *Accuracy and expert testimony*, Bulletin of the American Academy of Psychiatry and the Law, 20(1), 1992, pp. 69–79.

descriptive parts that 3D technology and printing have been in use for decades, applied across various industries, and represent a continually evolving field. Practice within forensic domains is also characterized by ongoing development and experimentation. One of the barriers to this progress is limited resources (as expensive equipment investments are necessary) and the low level of research time allocated. Thus, it can be said that, typically, only a few experts experiment with and apply modeling and printed objects as demonstrative tools in specific cases within Hungarian criminal proceedings; however, where applied, promising results and reception can be reported.

When examining the use of 3D models on a theoretical level, it becomes evident that the principle of fair trial arises from both the Constitutional Law and the Code of Criminal Procedure, as well as Article 6 of the European Convention on Human Rights, which affirms the right to defense, access to evidence, and the requirement of procedural transparency. As noted in the previous chapter,⁵² visual reconstructions may at times be overly persuasive, thereby potentially distorting evaluation and the perception of the accused. Therefore, in my opinion - and in the absence of further research findings - each case requires an assessment based on the principle of proportionality to determine which interest takes precedence: understanding the specific facts of the case or ensuring the impartial adjudication of the accused beyond a reasonable doubt.

5. CONCLUSION

The possibilities and limitations of 3D printing are equally noteworthy, particularly regarding the demonstrative use and preservation of evidence. While we highlighted as an advantage the ability to reproduce evidence, improve visualization opportunities during trial, and increase the accuracy of expert analyses, we also identified challenges, including the lack of unified legal regulation and unresolved issues concerning the authenticity of data.

Literature reviews have indicated that 3D printing is a widely applied procedure in several forensic domains, functioning as a demonstrative tool and as part of expert representations, including ballistic analysis of firearms, forensic anthropology, and crime scene modeling. Case studies accessed through online sources also demonstrate that the use of 3D models enables more effective and comprehensible evidence presentation for judicial actors. However, widespread application (as emphasized in the Frye test) may encounter obstacles in the absence of standardization and legal acceptance.

⁵² Baier et al., *op. cit.* note 5, p. 1230-1237.

Accordingly, there is a need in the future to standardize 3D-printed evidence, to examine the admissibility of 3D models, and to develop international protocols that address the questions of when and for what purposes 3D printing may be applied in forensic contexts, and how the authenticity and accuracy of models can be preserved while ensuring legal admissibility. The procedural classification, admissibility, and associated evidentiary processes and safeguards related to 3D models are currently subject to case-by-case consideration. This may result in unpredictability, particularly concerning expert and digital evidence, which - due to their potential for manipulation - require heightened scrutiny.

Based on the three examined hypotheses, the following conclusions can be drawn:
H1: 3D printing enhances the preservation of evidence by creating accurate and durable physical copies of fragile or perishable items, which can also be transported easily.

The results of the literature review support that 3D printing is an effective tool for evidence preservation, as bones and crime scene objects can be reproduced, thus maintaining the integrity of the original items. However, the reliability and accuracy of printed models depend significantly on the printing technology and the material used. Therefore, standardized procedures are required. The hypothesis is confirmed, as 3D printing significantly contributes to the preservation and archiving of evidence.

H2: The use of 3D replicas in court improves understanding among participants in criminal proceedings.

Courtroom applications show that 3D-printed evidence greatly aids jurors, prosecutors, defense attorneys, and judges in understanding the circumstances of a crime. Interactive models enable the exploration of causal relationships, verification of event sequences, and examination from multiple perspectives. However, attention must be paid to the potentially strong influence of such replicas. Nonetheless, the hypothesis is confirmed, as they demonstrably enhance comprehension and memory retention related to the case in question.

H3: Despite its advantages, the use of 3D printing technologies in forensic sciences poses challenges in terms of ethics and accessibility.

The study suggests the future exploration of a fourth hypothesis: that 3D technology may enhance the objectivity of evidence assessment, especially through visual and interactive representations. Beyond the ability to produce weapons or explosives, a key issue is the potential manipulability of 3D models, which could mislead judicial participants. Data security concerns also emerge as a major future challenge. Moreover, the acquisition of such technologies can be costly, further deepening the technological divide between developed and

developing countries. The hypothesis is validated, as numerous ethical and access-related issues arise that, without proper regulation, may hinder widespread application.

These validated hypotheses define future research directions, including comparative studies between traditional and 3D-printed evidence, as well as exploring the integration of technologies such as artificial intelligence with 3D printing. The reviewed studies demonstrate that virtual and augmented reality technologies are transforming forensic investigations, legal procedures, and crime scene analyses. Immersive and interactive technologies improve the accuracy of interpretation, allowing both legal professionals and lay participants to examine evidence more thoroughly. With VR, one can become virtually present at a crime scene, enhancing understanding of the case and facilitating the reconstruction of past events.

The combined use of 3D scanning, printing, and immersive technologies enables the preservation, analysis, and interpretation of crime scenes, improving evidentiary procedures and promoting fairer trials by reducing the impact of subjective factors.

In summary, the forensic application of 3D printing and related technologies not only supports investigation and litigation but also opens new dimensions for the administration of justice.

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