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PRESERVING DIGITAL CULTURAL HERITAGE FROM OBLIVION: PROCESSES, HARDWARE, AND SOFTWARE. ILLUSTRATED WITH SELECTED MUSEUM INSTITUTIONS IN POLAND

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Purpose: The article aims to compare activities of selected museum institutions concerning the protection of digital cultural heritage and offer recommendations for other museums in Poland based on the insights. Its focal point is conservation and digitisation practices as well as asset management processes in three organisations: two private museums and a museum affiliated with a university library.
Design/methodology/approach: The authors employed a qualitative approach in the form of case studies and desk research. Detailed accounts are provided of the processes in the three institutions, the Museum of Electronics in Kraków, the 'Good Old Retro' Museum in Gniezno, and the Central Library of the University of Agriculture in Kraków.
Findings: The authors identified challenges for all three institutions, such as limited access to spare parts, degradation of storage devices, and a shortage of qualified staff. Differences among them include the scope of activities and methods of presenting their collections to the public. The library concentrates on digitising its assets and building an online knowledge platform, while the museums preserve electronics and hold open, interactive exhibitions for visitors.
Practical implications: The results can be used as good practices for cultural institutions that face new challenges of protecting digital heritage, particularly restrictions linked to the limited availability of technical resources and qualified personnel.
Originality/value: The comparative analysis of three different models of digital cultural heritage management offers new research perspectives and suggests potential adaptation scenarios for diverse institutional contexts.
Keywords: digital heritage, cultural asset management, digitisation, digital library, hardware preservation, archiving.
Category of the paper: Research paper.

1. Introduction

As computer and information technologies boom, cultural heritage protection is gaining a new, digital dimension. At the same time, digital content carriers are becoming cultural heritage artefacts (Thwaites, 2013). An increasing number of cultural institutions, such as museums, libraries, and archives, face the challenge of protecting both tangible artefacts and those born digital together with associated metainformation. The challenges expanded beyond the preservation of material collections into the domain of digitisation and data migration, software and file format compatibility, and long-term storage (Yong, Gates, 2014).

According to the literature, a substantial part of researchers focus on large, international digitisation projects (Sangmeister, Villhauer, 2022). However, local initiatives by museums or libraries, often involving little funds and substantial effort from enthusiasts, are a critical source of insight into the practical aspects of hardware and software conservation. Despite the growing fascination with digitisation in academic and institutional circles, no comprehensive study offers a comparison of practical solutions regarding collections (hardware heritage and software heritage) and system solutions (organisation, regulatory concerns, and staffing) employed in institutions of various types, from technology museums to museums affiliated with university libraries. This poses a certain research gap worth addressing.

The article compares the activities of selected museum institutions concerning the protection of digital cultural heritage in Poland. The specific objective is to identify critical challenges of digitisation and long-term storage of digital assets, followed by recommendations for best practices. The analysis will identify effective methods for protecting digital heritage and offer recommendations that similar institutions could use to their benefit. Such analyses can contribute to sustainable digitisation and asset protection strategies on the local and national levels. The objectives were pursued by analysing and comparing actions taken by the three cultural institutions. The analysis covered the preservation of hardware heritage and software heritage (software and digital assets) (Król, 2021). The article investigates the following research questions:

RQ1: What standards and procedures do cultural institutions employ to ensure preservation and accessibility of digital assets?

RQ2: What good digitisation practices from the case studies could be implemented in other cultural institutions?

The article has been structured to promote an exhaustive presentation of the problems related to digital cultural heritage protection. The introduction sets the scene for the problem, unveiling the research gap, the objective, and the research questions. Next, the Background section provides a theoretical framework concerning digitisation, emulation, archiving, and data preservation. Materials and Methods offers the research design, specifically the case study and desk research methods. The body of the article investigates three case studies of cultural

institutions, including their conservation and digitisation practices. The discussion involves a comparative analysis of the activities: both similarities and differences referenced to the current literature reports. The article ends with conclusions and practical recommendations, followed by limitations of the study and potential further research.

2. Literature review

Protection of digital cultural heritage requires diverse methods to ensure long-term availability of hardware and data security (Table 1). Emulation is one of the fundamental tools. With emulation, users can run old software and read archaic file formats on modern terminals and operating systems (Lurk et al., 2012). Emulators provide access to digital resources created in frameworks that modern operating systems cannot handle. They can run obsolete games, applications, or interactive content in web browsers, for example. Emulation is particularly valuable for archives and libraries that store unique materials that can be read only with specific tools (Acker, 2021). It is a critical part of the protection toolbox for software heritage at risk due to technology changes.

Table 1.
Selected methods for preserving digital cultural heritage artefacts

Preservation method	Description	Literature references
Physical safety of equipment	Servicing, storage conditions monitoring, proper handling and maintenance, UPS systems as power sources	Król (2021); Lucchi (2023)
Data redundancy and archiving	Distributed backup systems, RAID systems, and offline backups	Thwaites (2013)
Long-term storage and data migration	Data migration into new storage devices and the cloud, and the use of future-proof file formats	Conway (2015); Adu, Ngulube (2016)
Cloud computing and digital repositories	Cloud storage, use of digital repositories	Teregowda et al. (2010); Król (2021)
Data standardisation and interoperability	Use of open metadata standards and data exchange protocols	Burns et al. (2019)
Content management systems	Use of CMSs and data integrity monitoring	Król (2020); Król, Zdonek (2022)
Cyberthreat protection	Use of firewalls, data encryption, two-factor authentication, and regular software updates	Vuković, Štefanac (2023)
Personnel education and training	Training on digitisation, archiving, CMS, and digital security	Achille, Fiorillo (2022); Jagielska-Burduk et al. (2021)
International and nationwide cooperation	Participation in international digitisation projects, cooperation with other cultural institutions	Charlesworth (2009); Dhonju et al. (2018)
Digitisation	Digitisation of analogue objects (documents, photographs, recordings, exhibits) to archive and protect them as well as exhibit them in a digital format	Taylor, Gibson (2017); Orphanidou et al. (2024); Remondino (2011); Kantaros et al. (2023)
Emulation	Accurate reproduction of the specific hardware or software system operation on another system. Use of emulators to run archaic software and files	Lurk et al. (2012); Acker (2021)

Cont. table 1.

Simulation	Reproduction of the operation of an actual system, phenomenon, or process in an artificial manner, most often with a computer. It focuses on functionality and operational logic, but does not have to duplicate the original technical environment	Cardellicchio et al. (2024); Garcia-Fernandez, Medeiros (2019)
Digital twins	Virtual models of actual objects, processes, or systems that reproduce their condition, behaviour, and interactions in real time	Pylianidis et al. (2021); Lucchi (2023)
Replicas, hardware clones, reproductions	Use of devices reproduced from originals to accurately represent the operation, appearance, or interfaces of the original equipment. Hardware clones use modern components to preserve compatibility with the original on the user and/or technical level	Burns et al. (2017)
Digital surrogates	Creation of digital representations of tangible items, processes, or persons for virtual analysis. They can be 3D models, avatars, or simulations	Conway (2015); Shao, Kibira (2018)

Source: original work.

Digitisation is the second pillar of digital heritage preservation. It means conversion of analogue items, such as books, documents, pictures, audio recordings, or even museum pieces, into digital counterparts (Kantaros et al., 2023). Digitisation prevents the destruction of assets and enables digital libraries or online museums to present them to a broad audience. The process involves special scanners, cameras, and digital asset management software (Parkoła et al., 2016). Three-dimensional objects are digitised with 3D scanners, which can generate virtual models of sculptures and other heritage objects (Kantaros et al., 2023).

Still, without suitable archiving and data storage methods, digitisation would be counterproductive. Backups in diverse formats and locations are critical for preserving assets. RAID systems (Redundant Array of Independent Disks) and regular backups on physical storage devices and in the cloud are an important part of the process (Teregowda et al., 2010). Another weighty consideration is data migration onto new storage devices and use of future-proof file formats that guarantee asset accessibility in the future (Poulopoulos, Wallace, 2022). Digital surrogates complement digitisation. These high-quality digital representations replace original documents and items in research, exhibitions, etc. (Conway, 2015). They help limit physical contact with vulnerable materials, which prevents degradation. Digital surrogates are used in museums and libraries to reconstruct lost historic artefacts.

Digital twins also merit a mention in this context (Pylianidis et al., 2021). These are virtual models of actual objects, processes, or systems that reproduce their condition, behaviour, and interactions in real time. With inputs from sensors and the Internet of Things (IoT), digital twins can be used to monitor, analyse, and simulate the operation of their physical counterparts. In cultural heritage conservation, digital twins are detailed and interactive 3D models of heritage items or sites that represent their appearance, structure, and condition (Lucchi, 2023). Combined with laser scanning, photogrammetry, and environmental sensors, digital twins can be used in change monitoring, conservation planning, and threat responding.

Another important issue in protecting digital assets from oblivion is metadata standardisation and ensuring interoperability of computer systems (Burns et al., 2019). Such standards as Dublin Core or OAI-PMH facilitate exchanging information among cultural institutions and integrating various digital collections. Cybersecurity is also an issue. It includes encryption, firewalls, multi-factor authentication, and threat detection systems. Attacks on critical server infrastructure and data loss pose a serious risk to the preservation of valuable heritage assets. Hence, regular updates and security systems are indispensable (Vuković, Štefanac, 2023).

Education and international cooperation are also vital for effective digital cultural heritage protection. Trained personnel of cultural institutions can implement new digitisation and archiving methods, while international partnerships provide platforms for exchanging good practices (Charlesworth, 2009). Such initiatives as Europeana and UNESCO Memory of the World support efforts towards preserving digital assets (Jagielska-Burduk et al., 2021). When combined, the methods can effectively preserve digital cultural heritage for posterity.

3. Methods

The study employs two primary research methods: desk research and case study. This approach facilitates a comprehensive analysis of digital cultural heritage preservation, focusing on maintenance, digitisation, emulation, and long-term data archiving (Bednarowska, 2015).

The desk research involved a review of the literature, specialist reports, and technical documentation relevant to digital asset protection methods. The authors concentrated on publications concerning digitisation, metadata standardisation, data migration, and preventing digital degradation of hardware and software. They further analysed guidelines of international organisations, such as UNESCO, that play the central role in drafting standards for digital heritage management (Charlesworth, 2009; Jagielska-Burduk et al., 2021). The desk research additionally investigated initiatives aimed at archiving Internet resources, such as the Internet Archive, and technologies supporting long-term data storage (Conway, 2015).

The other method was the case study. It analysed the practicalities of digital cultural heritage protection in selected cultural institutions: (1) the Central Library of the University of Agriculture in Kraków, (2) the Museum of Electronics in Kraków, and (3) the ‘Good Old Retro’ Museum in Gniezno. The inquiry into their activities allowed the authors to assess the hardware, software, and data archiving and digitisation processes. The focal point was tools for digitisation, emulation, and preventing degradation of digital assets, including digital decay and link rot (Król, Zdonek, 2019).

The joint application of desk research and case study yielded a structured approach to the research problem and identification of the most effective practices employed in the investigated museum institutions.

4. Results

4.1. Conservation efforts at the Museum of Electronics in Kraków and its Chorzów branch

The Museum of Electronics in Kraków is a unique institution set to preserve and display the technological heritage of the past decades, with Polish achievements in the spotlight. Its collection contains a variety of devices, from household appliances, TV sets, radios, amplifiers, and cassette decks, to gaming consoles, computers, and arcade machines. This diversity poses several challenges related to the conservation and maintenance of technical and operational characteristics.

One of the key problems is the unpredictable availability of spare parts. Many devices have universal components found in various models, which makes it easier to obtain and replace parts. These are cassette deck gears, vacuum tubes from TV or radio receivers, integrated circuits from diverse devices like Atari 65 memory chips, which are also used in PC XT, and many others. Still, despite the compatibility, many critical components are increasingly harder to obtain, so museums have to stockpile damaged devices for spare parts, or use substitutes or replicas. Therefore, the next challenge is to store large numbers of devices in appropriate conditions. Many objects have to be thoroughly cleaned when they are donated to the museum because they were stored in poor condition and exposed to dust, humidity, and corrosion. Leaking CMOS batteries (Complementary Metal-Oxide-Semiconductor) can cause corrosion and permanently damage printed circuit boards. If so, removing harmful substances and securing the device against further degradation is necessary. Limited storage space makes hardware selection and management particularly challenging.

The Museum of Electronics in Kraków actively collects and exhibits technology heritage, but also digitises it. The institution engages in creating digital reproductions of the assets it holds for long-term preservation and presentation for public consumption. It also develops multimedia, such as photographs, videos, technical descriptions, and 3D models to support interpretative and research efforts of the museum. This way, it preserves and promotes cultural heritage in a modern digital form (Figure 1).

Figure 1. Recording (filming) a part of the exhibition at the Museum of Electronics in Kraków. Source: Karol Król (December 2023).

Some part of the subassemblies kept at the Museum of Electronics in Kraków come from the stock of ELES, a former brand of the museum. However, many parts still have to be sourced from third parties. The contribution of the dynamically growing community of retro enthusiasts to the restoration of discontinued electronic components is noteworthy. One example is the new keyboard for ZX Spectrum available in two versions, an accurate replica and an upgraded flavour without the design flaws of the original. The SID chip from Commodore now has a digital substitute, SwinSID. Nevertheless, these solutions can be cost-intensive, which makes them scarce.

4.1.1. Reconstruction of details and wear and tear on exhibits

Not all components can be reproduced or replaced with modern counterparts. Such original details like radio knobs and switch or potentiometer trims are particularly hard to find, and they do get lost easily. Even substitutes are scarce. In such cases, enthusiasts look for the parts on flea markets, electronics markets, and among private collectors. Sometimes they also use substitute parts.

One of the principal premises of the Museum of Electronics in Kraków is to allow visitors to actively use the exhibits, which leads to wear and tear. Although game pads are at a particular risk, the museum strives to maintain their original form to keep the user experience authentic. The quality of the substitute components available on the market is often below that of the original products, which adds to the challenge. Modern GameCube controllers could not hold a candle to the models from a few decades ago in terms of durability.

Some devices are fragile and have to be handled skilfully, so they are not made available to visitors. For example, unique record players are particularly prone to damage. Their styluses were often broken due to misuse. Sometimes, even the tonearm could be broken. As a result, these devices were moved to higher shelves, and visitors can only interact with them on request and under supervision.

The Museum of Electronics in Kraków collects original software only. Regrettably, many storage devices degrade over time up to the point of being unreadable. Some programs can be restored from online archives, but physical storage devices, like cartridges or CD-ROMs, become useless over time. While some cartridges can be repaired by replacing damaged logic circuits, those in the worst condition can serve only as visual exhibits. The museum re-releases archaic computer games. One of them was ‘Mill’ re-released on a compact cassette for Commodore (Figure 2) with Stereo Style s.c. from Kraków.

(a) (b)

Figure 2. Interactive exhibition at the open days at Astor 2024. In the photograph, there is Łukasz Bazarnik, the curator and co-owner of the Museum of Electronics in Kraków (a). The museum reactivated an archaic game, Stefan Życzkowski's ‘Mill’, in 2024 (b).

Source: Król (2024).

Hard drives in older devices, such as Xbox consoles, require special effort, including removing security systems, to be replaced. Sometimes original disks can be replaced with more reliable technology, like Compact Flash cards, to improve the durability. Yet another problem is when visitors modify the software. It is sometimes by accident, sometimes purposefully, but always leads to system reinstallation and restoration.

It takes expert knowledge and access to documentation, which is often scarce, to repair heritage hardware. Many devices donated to the museum are missing manuals or service diagrams, which makes repairs challenging. Service experts are increasingly hard to find as well. Many of them consider such repairs a pastime, which means the process takes much longer. If repairs are outsourced to an unverified person, they can prove unqualified, damaging the device further, even beyond the point of repair.

The Museum of Electronics in Kraków with a branch in Chorzów deploys innovative solutions, combining archaic ‘physical interfaces’ with new technologies in interactive exhibitions. This approach is exemplified by the Maluch Simulator in Chorzów. Visitors can get behind the wheel of an authentic Fiat 126p and participate in virtual racing in Maluch Racer using original controls (Figure 3). This unique combination of physical experience and digital entertainment offers a deeper dive into the history of automotive and digital technologies, educating through fun.

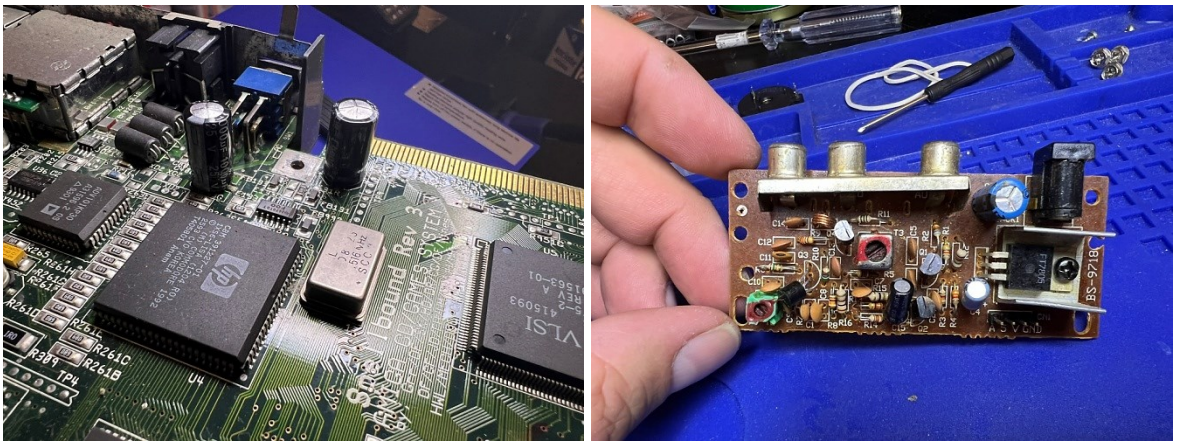
Figure 3. Fiat 126p Simulator cockpit. Museum of Electronics in Kraków, the Chorzów branch. Source: Król (2024).

It takes careful balancing of exhibit conservation and facilitating visitor interaction with the assets to run the Museum of Electronics in Kraków. The most critical challenges are the availability of spare parts, limited storage space, complicated servicing, high costs of repairs, shortage of experts, and daily damage caused by careless visitors. Despite these difficulties, the museum consistently works towards preserving and promoting technology heritage to allow future generations to experience the history of electronics in an engaging way.

4.2. Conservation at the ‘Good Old Retro’ Museum: methods and challenges

The ‘Good Old Retro’ Museum in Gniezno focuses on collecting, conserving, and presenting to the public electronics and software from past decades, particularly computing devices and gaming consoles. Its conservation process consists of numerous operations to restore the full functionality of devices and appropriately present them to visitors.

A newly donated device is first verified for completeness and condition. Most devices are acquired unverified, often with visible damage (Figure 4). The examination includes a visual inspection and electrical measurements. The worst dirt and leaks are removed at this stage. The next step is to assemble a system for a test run. Missing components, such as cables, monitors, power supplies, or input-output modules, often have to be found. Original parts are used, if possible. Otherwise, substitutes ensure visitors' access to operational equipment as a priority.

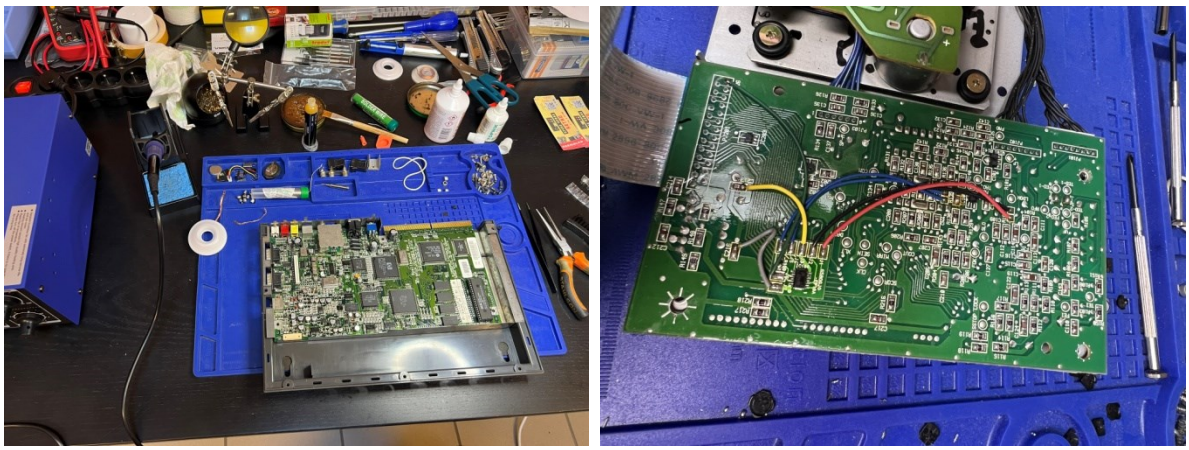


(a) (b)

Figure 4. Inspection of the motherboard of Amiga CD-32 (a), Check of the board of the BS500AS console (b).

Source: Andrzejewski, (2024-2025).

A complete system is test-run to verify its operational capacity. If some components are found defective, the device is repaired. It can have electronics replaced, PCB tracks regenerated, power supply restored, or mechanical components, such as push buttons or potentiometers, reconstructed (Figure 5). Sometimes, the latest technology is put to use, such as 3D printing, to restore missing structural elements.



(a) (b)

Figure 5. Inspection of the motherboard of Amiga CD-32 (a), Check of the board of the BS500AS console (b).

Source: Andrzejewski, (2024-2025).

Visual restoration is another milestone. Many exhibits are discoloured by time and use. The most common defect is the yellowing or greying of plastics. The white colour is restored with chemicals and UV radiation. Any cracks and other mechanical damage are also repaired. With conservation done, the device is catalogued and listed in museum records. The records include the origin, condition, and repairs, which helps with collection management and planning of future activities.

Ongoing conservation of exhibits is a critical part of the museum's efforts because of the wear and tear caused by visitors. Regular inspections and reports from users facilitate rapid response to damage, such as broken joysticks, defective disk drives, or distorted image on CRT (Cathode Ray Tube) monitors (Figure 6). The museum also takes care to safeguard the devices during transport, especially to and from special events.

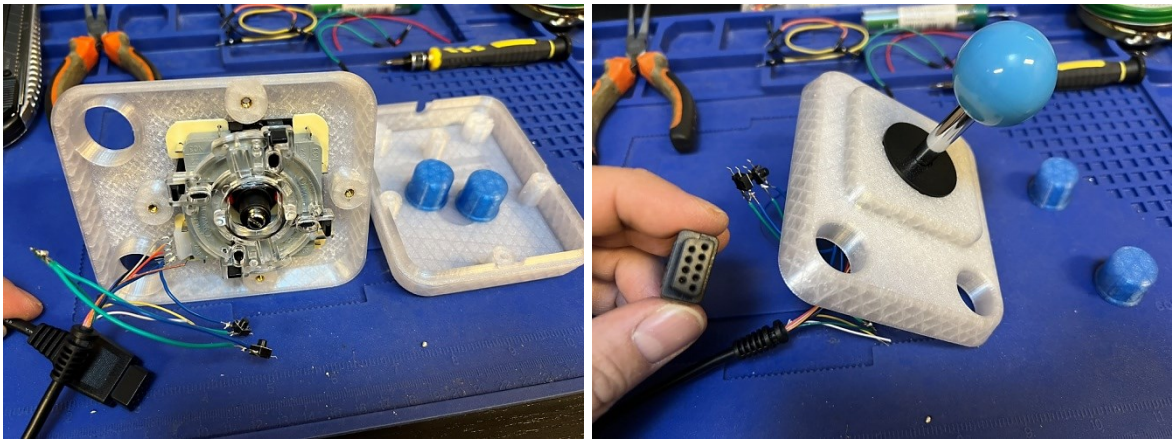


Figure 6. Assembling a custom-made arcade joystick.

Source: Andrzejewski, (2024-2025).

Software acquisition, archiving, and conservation are yet another important part of the museum's efforts. Storage devices: floppy disks, cartridges, compact cassettes, or CD-ROMs are verified in terms of operability, and their content is backed up on new carriers to preserve it. In addition to hardware and software, the museum collects literature and trade periodicals (Figure 7). Conservation includes cleaning, airing, fungal removal, cataloguing, and preparation for exhibition.

(a) (b)

Figure 7. Computer with the Museum DataBase, a program coded by the museum staff in BASIC, which offers printable details of the exhibits (a). Museum display cases and a reading corner (b).

Source: Andrzejewski, (2024-2025).

In the long-term perspective, the museum stockpiles hardware and components for spare parts and replacement exhibits. One particular element is CRT monitors and TVs. They are critical for the authentic retro experience. The conservation efforts at the 'Good Old Retro' Museum combine traditional methods and new technologies to protect technology heritage and keep the experience available for future generations of users at the same time.

4.3. Hardware, software and premises for digitising analogue artefacts at the Central Library of the University of Agriculture in Kraków

As digital technologies expand dynamically, protecting, documenting, and promoting cultural heritage becomes contingent on the digitisation of analogue artefacts. Appreciating the potential of this process, the University of Agriculture in Kraków deployed a system for digitising analogue assets: both archived documents and unique tangible objects.

The Central Library of the University of Agriculture in Kraków (the Library) has been engaged in building a digital platform for digital representations of analogue collections. One of the greatest values of analogue assets is their uniqueness in terms of 1) topics: agriculture, agricultural training, and environmental, technology, cultural, and rural matters; 2) geography: Kraków, Lesser Poland, southeastern Poland; 3) human resources: professors, researchers, and practitioners engaged in environmental and agricultural sciences, and 4) diversity: books, articles, photographs, posters, maps, documents, museum exhibits (objects), and video and audio recordings.

The concept for the digital platform is based on the Jagiellonian Digital Library, one of the largest institutions of this type, established in 2010, and on other digital libraries in the Digital Library Federation (DLF). The Library archivists followed the development of various digital archives, such as Zintegrowany System Informacji Archiwalnej – ZoSIA (Integrated Archival Information System), Cyfrowe Archiwum Społeczne (Digital Social Archive), or Social Archive of the University of the National Education Commission in Kraków, in search of good practices. One outcome of the concept and design efforts was the idea to digitise part of the museum's collection. This objective required adequate hardware and software. The endeavour yielded the project Lesser Poland Natural Science Platform (the Platform), which was accepted by the Voivodeship Board and received public funding in 2018. The historical resources of the Library, including archive materials and museum assets, were digitised in the project period, from 2019 to 2021.

4.3.1. Hardware used to digitise collections of the Library

One of the first goals of the Platform was to purchase equipment for digitising the assets and establish a digitisation centre. First, it was located in the Jubilee Building of the University of Agriculture (24/28 Mickiewicza, Kraków). When the university archive was overhauled, it was moved to the ground floor of the building (3 Klemensiewicza, Kraków).

The digitisation centre has an overhead archive scanner, Zeutschel OS Q1, offering significant digitisation capabilities (Figure 8). It can scan case-bound and saddle-stitched documents such as library collections, archive materials, and early printed books in A1 format. It can easily digitise individual documents, graphics, atlases, prints, photographs, or posters. The device has a CMOS RGB line sensor and outputs TIFF, multi-page TIFF, JPG, PDF and other file formats. Although scanning takes time, the process is highly optimised. The scanning time depends on the resolution; for 200 dpi, it is 3.5 seconds, but for higher values preferred for heritage items, it is longer. In addition to the 1.37×2.20×2.144 m tabletop scanner, the digitisation centre has a computer with dedicated software, two image processing stations, and furniture for storing large-format maps, posters, and images. Zeutschel OS Q1 made several hundred thousand scans over nearly four years with no major breakdowns. It is regularly serviced, and any minor operational failures are promptly addressed.

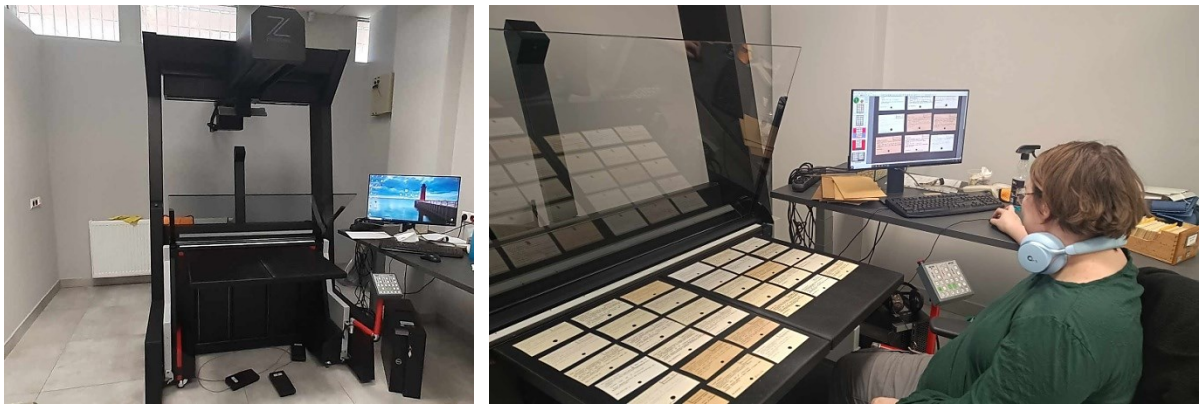


Figure 8. Zeutschel OS Q1 scanner in the digitisation centre of the University of Agriculture in Kraków Library.

Source: Urszula Gąsior and Agnieszka Góralczyk.

The Library has another, smaller scanner, Zeutschel Zeta Comfort, mainly for digitising A3 printed materials, such as books, prints, and articles (Figure 9). Its particular advantages include user friendliness (touch panel), scanning speed, and small dimensions. This compact scanner can make digital reproductions at 300 ppi in various formats, from TIFF to multi-page PDF. Thanks to the Perfect Book software, it can correct page curvature and remove shades and foreign objects from the scanned document.

In addition to the scanners, the Platform acquired a digital reflex camera, Nikon D850 (45.7 Mpx) with accessories, including two lenses: a fixed focal length and a zoom lens, and a 70×100×200 cm shadowless photography table with six umbrellas and lamps (Figure 9). This setup can take photographs of materials that are hard to scan. It is particularly useful for digitising 3D exhibits.

Figure 9. Zeutschel Zeta Comfort and Nikon D850 of the University of Agriculture Library in Kraków. Source: Paweł Jakubiec.

4.3.2. Role of software in digitisation

The other pillar of digitisation, in addition to hardware, is software. The Library has several such systems. The overhead scanner has special software, Omniscan 12.12, for operating the device and scanning. The process is controlled from a computer, but there is also a touch panel. Before the job, the operator sets up all scanning parameters, such as the scanning field, resolution, colour depth, and many others.

Digitisation can be automated with dLab by PCSS Dingo. This program can be used to configure individual jobs during scanning, types of activities, user groups, and reports. The Library employs dLab mainly for creating presentations of digital objects and archiving matrix files. dLab liaisons between the server for storing scans and dLibra. dLibra is an application for managing the website and a virtual workstation for the digital library administrator and editor. The server is an important component of the system because raw data and presentation files take up much storage. dLab is maintained by the University of Agriculture's IT Centre and the software provider.

dLibra is another component of the Lesser Poland Natural Science Platform. It comprises an application for the administrator, an application for the editor, and a website. The users use the software to store and manage the objects by modifying, grouping, assigning categories, and granting access rights. It supports sharing and managing the library, including user groups and their rights, and collaboration with other systems with such standards as OAI-PMH and RDF. dLibra has three general groups of users. The first are administrators who manage the library, create users, define their groups and rights, and create and modify the library's structure. They can access all subsystems, including statistics and visuals. The second group are editors. They build the digital library by adding objects and creating, importing, and grouping object descriptions. The last group are readers. They can access the library's website and published materials. dLibra facilitates work with materials available through the Platform, but requires training and practice.

The Library acquired ABBY FineReader PDF 15 licences for operators working on PDF files for correcting, modifying, and compressing documents. Graphic files can be processed thanks to Adobe Photoshop licences. With this package, the scans can be improved before uploading them to dLibra.

With its advanced hardware, the centre is used not only to digitise the library collection but also to hold presentations, training courses, and internships for archival sciences students, secondary school pupils, or archive, library, and museum staff who are interested in digitisation.

The digitisation centre continues its mission even though the project was discontinued in 2021. Regrettably, the Library does not have a dedicated digitisation team due to limited human resources, which is a standard in many libraries. Today, the Platform's effort is founded on an informal collaboration among employees of several Library divisions: Acquisition and Cataloguing, Archive, and Scientific Information and Documentation supervised by the Director. If time allows, the personnel modify and improve descriptions, add new items, and create new collections. The Library is ready to work with other institutions and individuals. Interaction with users yielded the publication of Granny Josie's Notebooks and documents donated by the family of Stanisław Juszczyk, the architect behind the Jubilee Building of the University of Agriculture in Kraków. They are available at the Library website in 'Member submissions'.

4.3.3. Premises for the digitisation of library and museum collections at the Library

The digitisation involved selected assets of the Central Library of the University of Agriculture in Kraków. These were such library collections as books, brochures, nineteenth-century prints, biographical envelopes with their content (such as press clippings); archive materials: nineteenth- and twentieth-century documents, documents from schools of agriculture, documents of the Faculty of Agriculture of the Jagiellonian University, photographs, posters, maps, and theses; occasional museum pieces: medals and badges; and equipment and devices: scales, apparati, and cameras.

Most of the items selected for digitisation under the Platform project were scanned with the Library's equipment (and dLab) and then processed in dLibra's administrator and editor applications. However, some of them had to be digitised by third-party experts because of their nature or dimensions. This process resulted in a collection of large-format posters and selected 160 museum exhibits. Three-dimensional GIFs of the pieces were obtained with 360° photography (144 images per object). The last items digitised by an external service provider were 3.1 thousand metres of 16 mm tape films. The thirty digitised films concerned special occasions, research, and instructional materials. The digitisation standards were consistent with those in digital libraries in Poland. The scans can be browsed through the Digital Library Federation after the Library is accepted as a member, thanks to the use of identifiers (OAI-PMH and RDF).

After the Platform website was established (https://mpnp.urk.edu.pl), the scans and their metadata were imported to the data server and assigned to collections. The team's intent was to display the typological diversity: periodicals, books, nineteenth-century literature and press, old prints, museum pieces, audiovisual documents, archived matter, and 3D objects. Other collections represent the author or place of storage: University of Agriculture, Archive, Museum, or the type of the collection, such as Online resources, or Member submissions. One significant modification of the Platform's system is the availability of scanned publications in the Omega-Psir Repository (REPO URK). Eventually, REPO was linked through a button leading to the collection Database of Scientific Achievement of the University of Agriculture in Kraków.

At the design stage, the Library team was quick to notice that the only feasible file formats for asset presentation were PDF for books and periodicals and JPG for photographs and other graphical content. Larger files, such as TIFF, took much longer to load or could not be loaded at all to the server or in the browser window. Therefore, the matrix files were uploaded to the server via dLab or temporarily archived on special disks. Apart from digitisation, the Platform project has achieved deacidification and fungal removal, repair, and binding of heritage assets. It was also an opportunity to purchase special-purpose cabinets for the largest items and a safe for the most valuable collections.

Thanks to the digital platform, the university can display cultural artefacts related to agricultural education in Kraków dating back to the nineteenth century. These books, over two centuries old, photographs, films, and museum exhibits were unavailable to a wider audience. The digitisation has contributed to establishing a knowledge platform offering unique resources kept at the Library, Archive, and Museum of the University of Agriculture in Kraków and presented as a digital library together with the publications in REPO. There are over 17 thousand items (over 40 thousand items with REPO) and several hundred thousand scans in the digital library. The platform has had over a million visitors since June 2021. There were over 70 thousand searches, and more than 13 thousand objects were viewed. These numbers demonstrate the reach of the collections available to only a few not so long ago.

5. Discussion

5.1. Comparison of the actions taken by the investigated institutions to preserve technology heritage

The three organisations, the Museum of Electronics in Kraków, the 'Good Old Retro' Museum in Gniezno, and the Central Library of the University of Agriculture in Kraków, employ different standards and procedures for preserving and displaying digital assets. Hardware repair and conservation are critical in this case, followed by digitisation and

emulation. Digitisation with high-end hardware and software is employed for documents and 3D objects. Emulation allows the museums to display obsolete file formats and programs. Metadata standards like Dublin Core and OAI-PMH support collection interoperability, while archiving procedures: backups, data migration to new storage devices, and future-proof file formats (TIFF PDF/A), preserve the assets (answer to RQ1). Moreover, the institutions invest in personnel training and work with other organisations, which promotes the flow of knowledge and collaborative problem solving.

Although the investigated institutions address the same problem of preserving technology heritage, they differ in goals, methods, and sophistication of digitisation processes (Table 2). The museum's focus is on physical conservation, repairing, and interactive presentation of exhibits. Both acquire hardware and maintain it with the help of the community and reused resources. In contrast, the Library is engaged primarily in digitisation. Using sophisticated equipment and software, it creates metadata and actively shares online resources on a digital platform. All of them preserve collections and educate their staff, each in its own way. The museums seem to prefer practical and interactive activities, while the library has training courses and publications. Therefore, the analysis demonstrates that comprehensive heritage protection requires physical effort in the tangible environment and digital work in the virtual space, preferably in a complementary and integrated manner.

Table 2.
Summary of activities taken by the investigated institutions

Operation	Museum of Electronics in Kraków (the branch in Chorzów)	'Good Old Retro' Museum in Gniezno	Central Library of the University of Agriculture in Kraków
Hardware and software acquisition	Yes, it collects hardware and software	Yes, it collects hardware and software	Yes, it acquires digitisation equipment
Hardware conservation and repairs	Yes, it repairs, cleans, and replaces components	Yes, it performs complete repairs	Yes, it performs physical conservation and ongoing repairs
Missing component reconstruction	Yes, it uses spare parts or substitutes	Yes, it uses spare parts or substitutes	No, no action to rebuild the equipment is taken
Digitisation	Partial, it mainly restores and revives software	Partial, it mainly restores and revives software	Yes, complete digitisation of assets
Data and metadata archiving	Partial, it collects documentation and keeps digital archives	Partial, it collects documentation and keeps digital archives	Yes, it creates metadata, generates descriptions, and catalogues assets
Digital asset presentation	No, it offers interaction on site, no online exhibitions	No, it offers interaction on site, no online exhibitions	Yes, the library uses the Platform and dLibra
Collaboration with other institutions/experts	Yes, it partners with the retro community, collectors, businesses, institutions, and media	Yes, it partners with the retro community, collectors, businesses, institutions, and media	Yes, it collaborates with institutions and users
Preservation of assets against degradation	Yes, it employs cleaning, protection against humidity and corrosion, and condition monitoring and responds to damage	Yes, it employs cleaning, protection against humidity and corrosion, and condition monitoring and responds to damage	Yes, it has digital storage and special-purpose cabinets

Cont. table 2.

Technical files	Yes, it catalogues the condition of assets	Yes, it catalogues the condition of assets	Yes, it keeps digital and descriptive documentation
Education and promotion efforts	Yes, it has interactive exhibitions, offers education through experience, and holds retro events	Yes, it delivers workshops, shows, and retro events	Yes, it has training courses, shows, and digital publications

Source: original work.

Despite different approaches, the three institutions face similar challenges. They have to overcome personnel limitations, address the unavailability of spare parts, and manage the degradation of storage devices. The museums more often face wear and tear on their 'exhibits' as they are worn down by users. The Library has to address the technological and organisational challenges linked to large-scale digitalisation efforts. Despite these difficulties, each institution effectively contributes to the preservation and popularisation of digital cultural heritage, demonstrating that involvement and collaboration with different stakeholders may compensate for hardware or financial limitations.

The investigation identified several good practices that other cultural institutions can implement (answer to RQ2). These are the integration of conservation and digitisation measures, development of digital platforms for publishing collections online, regular acquisition of components and creation of digital surrogates, and active expansion of institutional networks. Education of staff and end users is also an important factor. The recommendations are:

1. Integration of conservation and digitisation efforts. Museum institutions should combine physical protection, exhibition of assets, digitisation, and presentation in the online ecosystem. Digitisation and conservation should be considered complementary processes. Thanks to the former, the original artefact does not have to be exhibited, which reduces the risk of damage. The latter is a way to preserve the material authenticity and historical context of the asset.
2. Cooperation with local and international partners. Partnerships with organisations, enthusiasts, collectors, research centres and technology providers are particularly important. They enable the organisations to obtain components, technical documentation, and share knowledge and experiences.
3. Acquisition of spare parts and digital components. An inventory of old storage devices and software gives more flexibility in responding to failures or data loss.
4. Development of digital platforms and online catalogues. Systems, websites, and applications for collection management are necessary. They help exhibit assets to the wide public and limit the physical contact with originals, which reduces the risk of damage or wear.

5. Personnel training and visitor education. Staff competencies have to be developed, both regarding digital technology (hardware and software operation) and traditional, hands-on conservation of devices and programs. Additionally, visitor education helps reduce the risk of damage caused by ignorance.
6. Use of physical heritage interfaces in interactive exhibitions. The concept of combining original hardware elements, such as car dashboards, control panels, consoles, or parts of authentic cabins, of aircraft, for example, with retro software or games is worth pursuing. Physical contact with heritage interfaces, augmented with operational digital systems, can offer an immersive educational and museum experience that engages the visitor and better conveys the nature of interaction with past technology. Such hybrid installations can be modern heritage interpretation tools and vehicles for promoting technology heritage on a highly narrative and emotionally loaded level.

5.2. Challenges to artefact conservation and digitisation in international literature

Ensuring long-term availability and integrity of data is the most critical problem in digital cultural heritage protection. According to the literature, the primary challenges include degradation of storage devices and rapid technology ageing (Conway, 2015; Adu, Ngulube, 2016; Król, Zdonek, 2019), which is supported in reports from the investigated institutions. Hard disk drives, LTOs (Linear Tape-Open), or CD/DVDs come with limited service life and can be damaged. Moreover, the software necessary to read old files in past formats is often no longer supported or developed, which leads to issues such as software decay or data decay (Król, Zdonek, 2019). To address these problems, the investigated institutions migrate data to more modern storage devices and use future-proof file formats, such as TIFF or PDF/A (see Góralczyk, Jakubiec, 2023).

Another grave threat to the life of digital assets is data security. Cultural institutions are increasingly targeted by cybercriminals, including ransomware attacks, which can render digitised collections completely inaccessible. Taking lightly such security measures as data encryption, multi-factor authentication, or regular backups often leads to irreversible losses (Vuković, Štefanac, 2023). A lack of universal standards for data organisation and storage is also a challenge. Many digitisation projects use different file and metadata formats, which hampers integration and inter-institutional data sharing. The literature emphasises the need for adhering to standards like Dublin Core, OAI-PMH, METS, or MODS, which improve asset interoperability (Burns et al., 2019).

Digitisation is the most common method for protecting cultural heritage. It can preserve analogue assets in a digital form to be shared through digital libraries and ‘online museums’. It covers scanning books, documents, and photographs and creating 3D models of museum exhibits. The process involves overhead scanners, cameras, and special software for managing digitised collections (Góralczyk, 2024). Another essential approach is emulation, which helps

run older versions of operating systems and software to give access to digital resources created using technology that is no longer supported (Lurk et al., 2012).

Institutions also use content management systems for organising and long-term storage of data to improve the longevity of digital collections. It is done with such platforms as dLibra, Omeka, and Fedora Commons. Many institutions also keep the collections in the cloud, which minimises the risk of server failure (Teregowda et al., 2010; Król, 2021). Another popular solution is digital surrogates. They facilitate presentation and detailed analysis of digital copies of original documents or objects. Museums also employ physical and digital 3D replicas for viewing and studying heritage items to avoid the risk of damage (Conway, 2015; Shao, Kibira, 2018).

Digital cultural heritage is furthermore threatened by digital decay and link rot (link decay). Digital decay means the gradual degradation of digital data due to the ageing of storage devices, mechanical damage, read errors, or technology incompatibility. Data carriers can be damaged by improper storage conditions or hardware and software failures. Link rot occurs when hyperlinks to digital content no longer work because the target asset has been deleted, removed, or archived without a proper redirect (Król, Zdonek, 2019). As a result, digital sources, often referenced by various institutions and organisations, can become unavailable, leading to fragmented knowledge and loss of valuable resources. The literature emphasises the significance of online archiving as a method for tackling the problem. Such organisations as the Internet Archive and resource identification systems that employ permanent identifiers, for example DOI (Digital Object Identifier), ARK (Archival Resource Key), and PURL (Persistent Uniform Resource Locator), help preserve access to online content and minimise the impact of link rot. Preventive strategies, like data migration and redundant copies, will be critical in the long term to counter degradation of digital resources (Conway, 2015; Adu, Ngulube, 2016).

For the protection of digital cultural heritage to be effective, it requires new technologies, expert training, and inter-institutional, inter-sectoral, and international cooperation (Dhonju et al., 2018). Training of cultural institution staff helps improve digital collection management efficiency, and international partnerships foster exchange of experiences and best practices. Organisations like Europeana and UNESCO Memory of the World are central to promoting digital asset protection standards and facilitating their global accessibility. Still, the greatest challenge in the literature is to ensure long-term readability and integrity of digital data. Although digitisation is the primary protection method, emulation, data migration, and cloud storage play an increasingly important role. Therefore, focusing on developing metadata standards, security measures, and international cooperation will be critical for preserving digital cultural heritage for posterity.

6. Conclusions

The comparative analysis of the three institutions: the Museum of Electronics in Kraków, the 'Good Old Retro' Museum in Gniezno, and the Central Library of the University of Agriculture in Kraków, suggests conclusions for the practice of digital cultural heritage protection. Despite their inherent differences, each organisation takes specific actions to preserve unique cultural assets for posterity. The digital cultural heritage museums focus on physical conservation and repairs of retro hardware, often with spare parts from other devices. They also have interactive installations where visitors can use the artefacts. The Library puts the digitisation of its resources, metadata management, and digital asset presentation at the centre. It has sophisticated hardware and an integrated system for online presentation of collections.

All three institutions are highly committed to collection preservation, although they employ digital technologies to varying degrees. What they have in common is education in many forms: from training, workshops, and publications to the promotion of heritage and integration of 'retrofans'. Despite limited human and financial resources, all the institutions successfully pursue their mission to preserve technology and cultural heritage. Their examples demonstrate that effective protection of the assets requires combining traditional conservation methods, new digital tools, and cooperation with other organizations.

The study results can be of particular value to a broad range of experts in institutions tasked with protecting cultural heritage, especially digital cultural heritage, such as museums, libraries, and archives. The investigated good practices and guidelines regarding the integration of physical conservation and digitisation can serve as a point of reference for institutions planning to engage in digital protection of heritage.

Future research could encompass a broader scope of additional institutions in Poland and abroad and an in-depth analysis of the efficacy of specific digitisation and archiving methods. More quantitative studies could help estimate the body of challenges regarding the preservation of digital cultural heritage and better adaptation of the recommendations to particular institutional needs.

6.1. Limitations and further research

Despite the broad scope of the comparative analysis, the article has certain limitations. First, its primary methods are case study and desk research, which may struggle to reflect the whole palette of practices employed in other similar institutions. Second, the analysis covers only organisations situated in Poland, which bars any generalisation on an international scale. Third, the article does not include in-depth interviews with people responsible for technical operations or managing digitisation processes, who could elevate the interpretation of the results.

Future research should cover a larger pool of institutions, including state archives, research centres, and other private organisations that collect and protect digital assets. Another important future interest could be to analyse the performance of individual digitisation and archiving methods and establish a model of good practices for various cultural institutions to adopt. Quantitative research could help estimate the extent of challenges and needs regarding digital heritage preservation on a larger scale.

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