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NOVA SCHOOL OF SCIENCE & TECHNOLOGY

DEPARTMENT OF COMPUTER SCIENCE

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BSc in Computer Science

DEVELOPING SUPPORT FOR THE HERITAGE DIGITAL TWIN IN CONSERVATION

MASTER IN COMPUTER SCIENCE

NOVA University Lisbon
September, 2023

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Abstract

Current technological advances and tools are bringing multiple benefits to the conservation area. One of those innovations is the use of the Digital Twin concept in conservation studies, allowing researchers to see and interact with the most possible complete representation of the artefact, its spanning life cycle and enabling continuous updates. This concept allows quality access to an enhanced representation of the artefact, focusing on the capacity of layering multiple visual descriptions, on one integrated interface.

This work aims to create a system to the VICARTE research unit where the concept of Digital Twin is applied to conservation and restoration studies, where the main objectives are to preserve, protect and restore heritage artefacts. To achieve that, an initial prototype was built, which allows to insert, view, interact, and analyse the abundant data related to a few historical artefacts from the Fitzwilliam Museum and Palácio Nacional da Ajuda. Although most related data is very technical, we aimed to develop a web interface easily accessible for both researchers and the public.

The system includes a data storage structure, a database service, where multimedia data (e.g. pictures) and textual data about the artefacts are stored and organised. A website was also developed, focusing on providing enhanced interaction with artefacts' information for researchers and the public, enabling understanding and insight regarding the artefacts. To be able to transfer data from the website to the database service, and vice-versa, a server was also designed and developed.

Throughout the system development process, there were several evaluation moments. However, the most significant of these was the conducted usability study, which assessed the tool's functionalities and its satisfaction levels among users. The results of the study indicated that users generally found the application moderately difficult to use and reported average satisfaction levels when interacting with the application.

Keywords: Digital Heritage, Digital Twin, Digital Heritage Conservation, Heritage Artefacts, Digital Twin in Conservation Studies

Resumo

As ferramentas e avanços tecnológicos atuais estão a trazer múltiplos benefícios para a área da Conservação. Uma dessas inovações é o uso do conceito de Gêmeo Digital na área da conservação, permitindo aos pesquisadores ver e interagir com uma representação completa do artefacto, o seu ciclo de vida abrangente e possibilitar atualizações constantes. Este conceito permite qualidade de acesso a uma representação melhorada do artefacto, focando na capacidade de sobrepor múltiplas descrições visuais, numa interface integrada.

Este trabalho tem como objetivo criar um sistema, para a unidade de investigação VICARTE, onde o conceito de "Digital Twin"é aplicado a estudos de Conservação e Restauração, onde os principais objetivos são preservar, proteger e restaurar artefactos culturais. Para alcançar itso, foi construído um protótipo inicial, que permite inserir, visualizar, interagir e analisar os abundantes dados relacionados a alguns artefactos históricos do Museu Fitzwilliam e do Palácio Nacional da Ajuda. Embora a maioria dos dados relacionados seja bastante técnica, o nosso objetivo foi desenvolver uma interface web facilmente acessível tanto para os pesquisadores quanto para o público em geral.

O sistema inclui uma estrutura de armazenamento de dados, um serviço de base de dados, onde são armazenados e organizados dados multimédia (por exemplo, imagens) e dados textuais sobre os artefactos. Também foi desenvolvido um website, com foco em proporcionar uma interação aprimorada com as informações dos artefactos para os pesquisadores e o público, possibilitando a compreensão e o discernimento sobre os artefactos. Um servidor também foi concebido e desenvolvido, para ser possível transferir dados do website para o serviço de base de dados e vice-versa.

Ao longo do processo de desenvolvimento do sistema, ocorreram vários momentos de avaliação. No entanto, o mais significativo destes foi a avaliação de usabilidade do sistema, que avaliou as funcionalidades das ferramentas e os níveis de satisfação entre os utilizadores após usarem a aplicação. Os resultados do estudo indicaram que os utilizadores, em geral, consideraram a aplicação moderadamente difícil de usar e relataram níveis de satisfação médios ao interagir com a aplicação.

Palavras-chave: Herança Digital, Gémeo Digital, Conservação da Herança Digital, Artefactos com Património, Gémeo Digital na area da Conservação

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Acronyms

3-TIER 3-Tier Application Architecture *(p. 40)*

AI Artificial Intelligence *(p. 25)*
AR Augmented Reality *(pp. 25, 29, 31)*

CRM Conceptual Reference Model *(p. 20)*

DB database *(p. 3)*
DBMS DataBase Management Systems *(p. 27)*
DCMI Dublin Core Metadata Initiative *(p. 8)*
DT Digital Twin *(pp. 1, 2, 13, 14, 17, 18, 23, 29–31)*
DTC Digital Twin Construction *(p. 17)*
DTD Digital Twin Data *(pp. 14–16)*

EDM Europeana Data Model *(pp. 20–22)*

GDH Global Digital Heritage *(p. 7)*

HBIM Historic Building Information Modelling *(pp. 12, 27, 30)*
HTML HyperText Markup Language *(p. 44)*

IIoT Industrial Internet of Things *(p. 25)*
IoT Internet of Things *(pp. 10, 11, 13, 17, 23, 25–27)*

JS JavaScript *(pp. 43, 44)*

NDIIPP National Digital Information Infrastructure and Preservation Program *(p. 8)*

REST Representational State Transfer *(p. 32)*

TS TypeScript *(p. 44)*

1

Introduction

This chapter provides an introduction to the problem that we intend to solve. First, Section 1.1 presents the motivation behind the work and Section 1.2 has a detailed description of the context of the problem (digital twin to support heritage in conservation). It also presents, in Section 1.3, the main objectives for this work and the problem that is intended to be solved, and Section 1.4 explains the contributions of the developed system. Lastly, Section 1.5 briefly lists the structure of the document.

1.1 Motivation

Wherever we are crossing a street, driving a car, or even staying at home, we are always surrounded by art in its various forms. Most people resort to enjoying diverse types of art when they want to improve their mood or immediately after something difficult occurs in their life, music being a great example. When travelling, most tourists will go to museums, cathedrals or just to "old" hamlets, to learn a little about the past and history of the place they are visiting. The same thing is true for sculptures, paintings, and music, since people also try to know more about the author of the pieces, their past and sometimes even try to understand why such piece was created.

Relevant issues about artworks are very diverse, and may include: 1) How, where and with which materials was the piece created? 3) What is the history behind this particular artefact? 2) How many times was the piece restored? 3) How was it restored, with which materials and in what specific zone of the artefact? 4) What changed from its original state? These are just a few of the many relevant questions when talking about cultural artefacts, which, until recently, have been mostly spread across in dossiers and folders, hindering the work of conservators and researchers.

The concept of Digital Twin (DT), explained in detail in Section 2.2, has been introduced and used in different domains, like health and infrastructure, and is currently starting to be applied in the conservation area. The ongoing advancements in digital twin technologies opened up the opportunity to develop systems for previously unexplored areas, such as the conservation of artwork pieces. This concept supports a comprehensive

digital representation of a relevant artefact, enabling the preservation of every data extraction, every new piece of information about it, thus documenting and preserving it indefinitely[2].

In this work, a support for art heritage Digital Twin is being developed, focusing specifically on enamels and glazes (since these pieces were the ones with much data available) and what could be done to study their state of preservation, production techniques and materials, and fundamental information for their effective conservation. Another objective of the work is to provide a structured way of safeguarding all the specific data collected on the artefacts, which contains how the studied artefacts were created (and with what materials), produced and preserved.

1.2 Context

The current dissertation aims to contribute to support the work developed in the VICARTE[1] Research Unit and Department of Conservation and Restoration[2] (DCR) of NOVA School of Science and Technology[3] (FCT NOVA), by developing an initial prototype of the Heritage Digital Twin for Conservation Studies enabling viewing, interacting and analysing associated artefact data. The DCR of FCT NOVA has the mission of teaching and researching in order to contribute to a better conservation and heritage enjoyment by present and future generations. DCR believes that a passion for research and an enthusiasm for heritage conservation and restoration should be shared with its students and the general public[3].

This project involves a multidisciplinary team that includes, as previously mentioned the DCR, the VICARTE, the Department of Computer Science[4] (DI) of FCT NOVA and the NOVA Laboratory for Computer Science and Informatics[5] (NOVA LINCS). This research teams intends to improve the structure and availability of the complete documentation and information of historical objects or their representations (for example a 3D diagram or a DT project), allowing a safe interaction with them. A infrastructure to collect and to interact with artefacts was designed and developed using enamels from the Fitzwilliam Museum[6] and glazed painted ceramics from Palácio Nacional da Ajuda[7], using data made available by VICARTE, using various different techniques such as UV-Visible Spectroscopy[8] and elemental analysis by X-ray μ-Fluorescence[9].

[1] https://vicarte.org/
[2] https://www.dcr.fct.unl.pt/departamento
[3] https://www.fct.pt/
[4] https://www.di.fct.unl.pt/
[5] https://nova-lincs.di.fct.unl.pt/
[6] https://www.fitzmuseum.cam.ac.uk/
[7] http://www.patrimoniocultural.gov.pt/en/museus-e-monumentos/dgpc/m/palacio-nacional-da-ajuda/
[8] https://www.technologynetworks.com/analysis/articles/uv-vis-spectroscopy-principle-strengths-and-limitations-and-applications-349865
[9] https://www.xos.com/Micro-XRF

The Fitzwilliam Museum is the art and antiquities museum of the University of Cambridge, was founded in 1816 under the will of Richard FitzWilliam, 7th Viscount FitzWilliam (1745–1816)[10], and comprises one of the best collections of antiquities and modern art in Western Europe. This collection comprises over 500k objects and artworks. The displays in the Museum explore world history and art from antiquity to the present, featuring artworks by renowned artists such as Monet[11], Picasso[12], Vincent van Goghh[13], and others[4].

The other pieces of art used in this work are painted glazed ceramics that belong to the Palácio Nacional da Ajuda. Some of these ceramics are thought to be painted by different members of the Portuguese Royal Family, such as King Ferdinand II[14] and D. Maria Pia[15]. The Palácio Nacional da Ajuda, a former royal palace and a national monument, is a magnificent museum and the only palace that can be visited in Lisbon. The Palace houses important collections of 18th and 19th century decorative arts: gold and silverware, jewellery, textiles, furniture, glassware and ceramics, as well as collections of paintings, engravings, sculpture and photography[5].

1.3 Problem Description & Objectives

The aim of this work is to design a comprehensive structure for the Heritage Digital Twin in Conservation studies, based on a structure to store all the available artefacts' data and provide innovative ways of delivering that data to the researchers, so that they can do their work more efficiently. Conservation and restoration processes are not generally known by the public, but they are detailed, difficult and demanding tasks, led by extremely qualified personnel, involving the analysis of large volumes of data. These data need to be organised, structured and maintained in relation with quality representations of the artefacts.

The process of creating a digital twin of an artwork has several goals, where not all of them were completed or even started in this dissertation but which will be addressed in future work. The first steps involved analysing several types of relevant artefacts, which some may occupy large volumes of data, that were collected or generated and structured in database format, according to the needs of the research teams. After the design and implementation of the database (DB) and also thinking of the future work, three main types of data can be stored in the current system and which are:

1. Pictures and diagrams describing the carried-out processes and the artefact itself;

[10] https://en.wikipedia.org/wiki/Richard_FitzWilliam,_7th_Viscount_FitzWilliam
[11] https://en.wikipedia.org/wiki/Claude_Monet
[12] https://en.wikipedia.org/wiki/Pablo_Picasso
[13] https://en.wikipedia.org/wiki/Vincent_van_Gogh
[14] https://en.wikipedia.org/wiki/Ferdinand_II_of_Portugal
[15] https://en.wikipedia.org/wiki/Maria_Pia_of_Savoy

2. Pictures of the artefact and important localised information allowing visualisation from diverse perspectives, but also to view several layers of information;

3. Equipment information used to retrieve the artwork pictures and related information, as well as PDF files containing additional details about the artwork in question.

With meticulous organisation, the data was structured, curated, and made more accessible and better organised. This ensures the data can effectively support future analyses and reflections on the evolution of artefacts. The application of the Digital Twin concept, when applied with our gathered data, will enable the representation of objects such as sculptures and paintings.

1.4 Contributions

At the end of the following dissertation the main expected contributions of the developed work are:

1. A comprehensive data structure to organise all the information regarding the considered artefacts and their exhaustive details.

    a) A data model that involves multimedia data, like pictures with different light frequencies and transparencies, as well as textual data.

    b) A preliminary set of tools to interact with the data in 1a.

2. An outcome evaluation led by qualified personnel based on a group of chosen artefacts.

3. Validation of the implemented tools through evaluation from researchers in the conservation area.

1.5 Document Structure

In this subsection it is presented the 7 chapters in which the document is divided:

- **Chapter 1 – Introduction:** The first chapter introduces the problem that we propose to solve. It presents why Digital Twin is a good option for the conservation and restoration of heritage artefacts, as well its problems and objectives. It is also mentioned the expected contributions and the structure of the document itself.

- **Chapter 2 – Fundamental Concepts:** The chapter provides a theoretical and technical introduction to the main important concepts related to our work. It is presented the concept of Digital Heritage, Digital Twin and Digital Heritage Metadata and their sub-themes. Furthermore, contains information in the best ways to gather and organise data to build a future digital twin.

- **Chapter 3 – Related Work:** In this chapter are presented some examples of applications/systems related to our work which gives some insight about their implementation and the importance of Digital Twin in different areas.
- **Chapter 4 – Solution Concept:** The chapter gives a detailed description of the solution concept, its structure and used technologies for the application conception. In addition, the functional and non-functional requirements are addressed, as well as the initial designed prototype.
- **Chapter 5 – System Implementation:** The chapter contains the main components of the developed system and exhaustive information how they were implemented according to the requirements brought up earlier.
- **Chapter 6 – Evaluation and Results:** In this chapter is introduced the evaluation and validation of the implemented system. It acknowledges the tests done, their results and what could be improved.
- **Chapter 7 – Conclusion and Future Work:** The last chapter overviews the carried out work along the dissertation, discussing its design and implementation. It also briefly introduces the future work that will be done to evolve the current version of the proposed solution into an actual digital twin.

2

Background Concepts

In this chapter the main concepts that are the foundation of this work are presented to help the reader understand more about the approached topics before existing practical work is presented in Chapter 3. Main concepts, such as Digital Heritage in Section 2.1 and Digital Twin in Section 2.2 are introduced, but also some other concepts related to those two. In the last Section 2.4 there is a brief summary about the presented concepts and their relation with the related work.

2.1 Digital Heritage

In the last few years, more exactly the last two decades, the democratisation of technology and its related features has made it possible to discover many new tools or adapt old ones. One example is the conversion of analogue resources to digital ones in very different areas such as resources of human knowledge or expression, whether cultural, educational, scientific, and administrative, or embracing technical, legal, medical, and other kinds of information. Nowadays, if resources are generally created digitally, no other support needs to be created[6].

Heritage is explained by United Nations Educational, Scientific and Cultural Organisation (UNESCO)[1] being "our legacy from the past, what we live with today, and what we pass on to future generations", something that is passed from generation to generation because its valuable[7]. UNESCO also describes Digital heritage as computer-based materials of enduring value that should be kept for future generations and which emanate from different communities, industries, sectors, and regions. Not all digital materials are of enduring value but, those that are, require active preservation approaches, if continuity of digital heritage is to be maintained. Another way to contribute to even faster growth in digital heritage is the development of tools to support greater multilingual and multi-script usage on the internet in parts of the world that are disadvantaged by English being the most widely used internet language.

[1] https://www.unesco.org/en

The need to safeguard this relatively new form of documentary heritage calls for international consensus on its collection, preservation and dissemination[8] and, as such, UNESCO stepped in and developed and adopted the "UNESCO Charter on the Preservation of the Digital Heritage" guidelines, which will be explained in the next Subsection 2.1.1. To support UNESCO in such a difficult job, some non-profit organisations were created. This is the case of Global Digital Heritage (GDH)[2], which is a not-for-profit, private research and education organisation dedicated to documenting, monitoring, and preserving our global cultural and natural heritage[9].

2.1.1 Digital Heritage Preservation

Digital preservation can be seen as all those processes aimed at ensuring the continuity of digital heritage materials for as long as they are needed. To do this involves finding ways to represent what was originally presented to users by a combination of software and hardware tools acting on data[10]. For this to be possible, digital objects must be understood and managed at four levels:

1. As Physical phenomena.
2. As Logical encoding.
3. As conceptual objects that have meaning to humans.
4. As set of essential elements that have to be preserved so future users can experience the essence of the object.

Due to natural disasters or man-made destruction during wars, a large volume of precious historical sites and artefacts have been damaged beyond repair. Rebuilding cultural heritage sites and artefacts is very difficult due to time, cost, and the lack of information about their original state. It can be compared to solving a large jigsaw puzzle without knowing what it should look like. While the importance of preserving cultural heritage is obvious, there are still many difficulties in the preservation process, which is where AI and other cutting edge technologies can help tackle some of those problems[11]. There are already some applications being developed and used in the field, such as RePAIR[3] (Reconstructing the Past: Artificial Intelligence and Robotics meet Cultural Heritage) and Scan4Reco[4], both resulting from EU-funded[5] research projects that apply robotics, 3-D scanning, and machine learning algorithms to restore and preserve cultural and digital heritage.

[2] https://globaldigitalheritage.org/

[3] https://cordis.europa.eu/project/id/964854

[4] https://cordis.europa.eu/article/id/248968-digital-surrogates-assist-in-the-preservation-of-cultural-artefacts

[5] https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/funding-programmes-and-open-calls_en

The UNESCO Charter on the Preservation of the Digital Heritage states that the purpose of preserving the digital heritage is to ensure that it remains accessible to the public. Accordingly, access to digital heritage materials, especially those in the public domain, should be free of unreasonable restrictions. At the same time, sensitive and personal information should be protected from any form of intrusion[6]. In this charter, article 6, it is explained how to develop strategies and policies to preserve the digital heritage according to the level of urgency, local circumstances, available means, and future projections. Lastly, article 7 describes which documentary heritage should be kept, and since principles vary from organisations and countries, it was decided that the "born digital" materials always should have priority and others would need to be reviewed by an assigned board.

Besides UNESCO and the EU, there are other institutions working towards digital preservation and heritage preservation. One example is GDH, as was mentioned before, uses digital visualisation, 3D virtualisation, geospatial informatics, and open access solutions to provide digital data and models to anyone. One of their missions is "the democratisation of science-we make all data freely available to the world in support of cultural heritage, heritage management, education, public access, scientific research, and to enhance the digital humanities"[9].

Alongside GDH also exists a website dedicated to preserve the digital heritage, which is hosted by the Library of Congress of the United States of America[6] and presents information about the National Digital Information Infrastructure and Preservation Program (NDIIPP) and its initiatives[7]. In addition, the Dublin Core Metadata Initiative (DCMI)[8] is a community of metadata professionals and practitioners that share an open and forward-looking ethos of "innovative practice". This "innovative practice" means bridging established metadata practices and graph-based solutions for integration across data silos[9] within a "Linked Data ecosystem"[12]. Some of the work of the Dublin Core will be shown in Section 2.3.

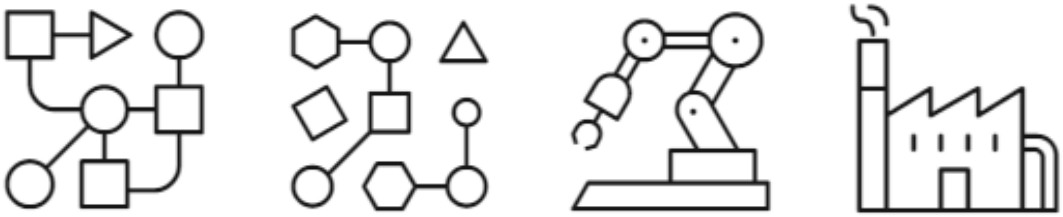
2.2 Digital Twin

The concept of Digital Twin (DT) technology is not entirely new, although only gained more recognition and popularity in the last few years. Its concept was designed in 2002 at the University of Michigan by Michael Grieves[10], an internationally renowned expert on Digital Twins, in relation to Product Lifecycle Management (PLM)[11]. The proposed model, which was referred as 'Mirrored Spaces Model', had three components: real space, virtual space, and a linking mechanism for the flow of data/information between the two[13].

[6] https://www.loc.gov/
[7] https://www.digitalpreservation.gov/
[8] https://www.dublincore.org/
[9] https://www.talend.com/resources/what-are-data-silos/
[10] https://www.linkedin.com/in/michael-grieves-6165719
[11] https://www.sap.com/insights/what-is-product-lifecycle-management.html

A digital twin is a virtual model designed to accurately reflect a physical object. The object being studied, for example, a wind turbine, is outfitted with various sensors related to vital areas of functionality. These sensors produce data about different aspects of the physical object's performance, such as energy output, temperature, weather conditions and more. This data is then relayed to a processing system and applied to the digital copy[14]. Based on the previous information, a digital twin fundamentally serves two main purposes. The first is preservation, which involves storing the information related to the object's entire evolution, using various methods as described later. Its other function is real-time monitoring of the object, which can be executed in several ways depending on the digital twin's specific objectives.

There are different types of Digital Twins depending on the Product scaling level, with the primary distinction lying in their areas of application[14]. It is extremely common to have multiple twins co-existing in the same system (object) or process. There are four different types of twins: first, **Component twins/Parts twins** are the basic unit of digital twin, being the smallest example of a functioning component, that is Figure 2.1a. Then **Asset twins** are when two or more components work together, enabling the study of the interaction of those components, and creating a wealth of performance data that can be processed and then turned into actionable insights, in Figure 2.1b. **System or Unit twins** enable different assets coming together to form a system, that provide visibility between the interaction of assets and suggest performance enhancements, and can be seen in Figure 2.1c. Lastly, **Process twins** reveal how systems work together and can help determine precise timing schemes that ultimately influence overall effectiveness, shown in Figure 2.1d.



(a) Component Twins (b) Asset Twins (c) System Twins (d) Process Twins

Figure 2.1: Types of Digital Twins[14].

One characteristic that binds most definitions of DT, other than being a virtual representation of a physical object, is the bidirectional transfer or sharing of data between the physical counterpart and the digital one. This transfer includes quantitative and qualitative data (related to materials, manufacturing process, etc.), historical data, environmental data, and most importantly, real-time data[15]. Using these data DT, can perform such tasks as:

- In-depth analysis of the physical twin;
- Design and validation of new or an existing product/process;

- Simulate the health conditions of the physical twin;
- Increase safety and reliability of the physical twin;
- Optimisation of part, product, process, or production line;
- Track the status of the physical twin throughout its lifetime;
- Predict the performance of the physical twin;
- Real-time control over the physical twin.

The main reason DT technology is seen as the cornerstone in Industry 4.0 is the numerous advantages it brings, including the reduction of errors, uncertainties, inefficiency, and expenses in any system or process[15]. Some of the reported advantages are:

- Speed prototyping as well as product re-designing;
- Cost-effectiveness;
- Predicting Problems/System Planning;
- Optimising Solutions and Improved Maintenance;
- Accessibility, since the physical device can be controlled and monitored remotely using its DT unlike physical systems;
- Safer than the Physical Counterpart, since in some industries like oil, gas or during COVID-19 would be safer to interact remotely using the DT instead of the physical object;
- Waste Reduction;
- Documentation and Communication, since to create a DT it is important to synchronise data from different databases, hard copies, etc, simplifying its access and maintaining it in one place;
- Training, since DT can be used to develop more efficient and illustrative safety training programmes than the traditional ones.

2.2.1 Internet of Things

The Internet of Things (IoT) is an emerging topic of technical, social, and economic significance. Consumer products, cars, industrial components, sensors, and other everyday objects are being combined with Internet connectivity without requiring human-to-human or human-to-computer interaction[16]. By the end of 2021 12.2 billion IoT devices were connected having a growth of 8% from 2020, and a growth of 18% was expected for 2022 resulting in 14.4 billion active connections[17].

Within the realm of the Internet of Things (IoT), various entities or "things" come into play. These include people equipped with heart monitor implants, livestock tagged with biochip transponders, vehicles integrated with sensors for monitoring tire pressure, or any other object, whether natural or artificial, that can be allocated an Internet Protocol (IP) address and is able to transmit data across a network[18].

At the same time, however, the IoT raises significant challenges that could stand in the way of realising its potential benefits. Attention grabbing headlines about the hacking of Internet connected devices, surveillance concerns, and privacy fears already have captured public attention. Technical challenges remain and new policy, legal and development challenges are emerging[19].

Recent advances in the IoT area and other technological areas made possible:

- **Access to low-cost, low-power sensor technology.** Affordable and reliable sensors are making IoT technology possible for more manufacturers;
- **Connectivity.** Net protocols that made it easy to connect sensors to the cloud or other "things";
- **Cloud computing platforms.** The increase in the availability of Cloud platforms enabled applications to scale up without the need for the management of the scaling process;
- **Machine learning and analytics.** The data from machine learning and analytics and cloud platforms can gather insights faster and more easily;
- **Conversational artificial intelligence (AI).**Advances in neural networks have brought natural-language processing (NLP) to IoT devices (such as Alexa, Cortana, and Siri) and made them affordable, and viable for home use.

In the last years, the growth in the IoT area is one of the parts that made possible the use of Digital Twins. As explained before, DT are virtual representations of physical devices/objects and can be used to run simulations before the devices are built and deployed. Since IoT devices are evolving, DT can include smaller and less complex objects, bringing additional advantages to companies. DT can also be used to predict different outcomes based on variable data where a scenario may be proven by a digital environment[20]. Nowadays, DT has moved past manufacturing, starting to take real-time IoT data and applying it in different areas such as AI and data analytics. Lastly, using additional software and data analytics DT can optimise IoT deployments for maximum efficiency, help designers deciding where "things" should go or know how "things" operate before they are physically deployed.

2.2.2 Heritage Digital Twin

First, an introduction to Building Information Modelling (BIM) must be done so the following information can be understand. BIM is a process for managing and creating

information on a construction project throughout its whole life cycle. This process includes a coordinated digital description of all the aspects built is developed, using appropriate technology. The digital description may include a combination of "*information-rich 3D models and associated structured data such as product, execution and handover information*"[21].

Data structuration in a Historic Building Information Modelling (HBIM) model needs to be reviewed so it can integrate the very specific aspects of Heritage Conservation such as the heritage significance, legal status, and actual condition of assets. The main objective is to bridge the gap between the different phases of an asset's life cycle, as well as ensure and strengthen the impact of preliminary studies in the decision making processes. The application of the DT concept based on a HBIM digital model containing such valuable information could eventually lead to assisted or automatic identification of hazards and technical solutions for a more efficient and wise preventive conservation of heritage assets[22].

Although there are additional examples in Chapter 3, here is presented a work directly related to Cultural Heritage Preservation using the concept of Digital Twin. The Digital Twin Lab of CITERA is developing a Virtual Model (DT) of the ancient Palace Silvestri-Rivaldi[12], a renaissanse resource strategically positioned next to the archaeological area of the Roman Forum. The building is going through an important intervention of rehabilitation managed by DGERIC[13] and involving many research and academic institutions through the innovative approach of the restoration yards schools: it is an experience of training by doing where the job of restoration, the job of cultural heritage surveying and several other workshops represent a unique opportunity to enter this extraordinary building and to participate to its rehabilitation[23].

The DT Lab research on Virtual Interactive Tour is using 360-degree camera along the Villa Silvestri-Rivaldi frescoed rooms where each Cultural and artistic resource is linked to hypermedia objects: BIM models, multimedia documentation and a systemic storytelling aiming to involve both technical and touristic users. The idea is to increasingly connect the hypermedia objects to a Blockchain database that would be able to certify historical data, maintenance Guidelines, instructions, and technical knowledge.

2.2.3 Product Life Cycle Phases

Data resources are a crucial need to develop and support digital twins. One of the key technologies in the new paradigm shift is called servitisation[14], in which companies start to offer services instead of one-off sale products. In all products/services there are three main life cycle phases:

1. Beginning of Life (BOL).

2. Middle of Life (MOL).

[12] https://pt.wikipedia.org/wiki/Palazzo_Silvestri-Rivaldi
[13] https://dger.beniculturali.it/
[14] https://www.nexsys.co.uk/knowledge-hub/servitization-jargon-buster/

3. End of Life (EOL).

In Figure 2.2, it is possible to see the three different life cycle phases with their respective processes and activities for each phase.

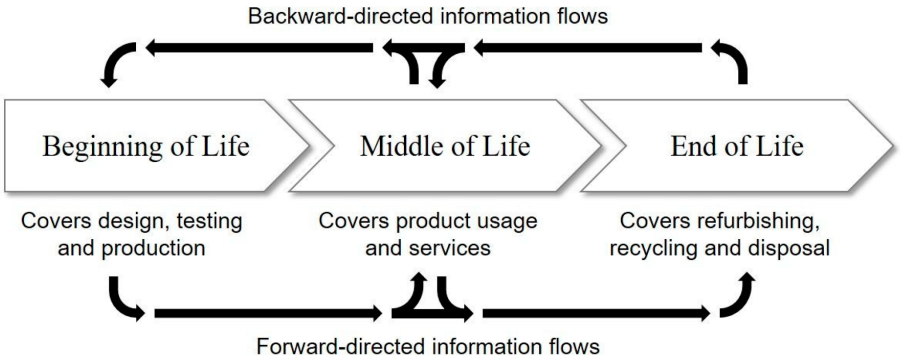


Figure 2.2: Stages of the product life cycle[24]

In the BOL phase there are plentiful data, usually called as "BOL data", which mostly includes 3D Models, mathematical models and planned factories. Although, the amount of data is enormous, it is only a digital model (DM), at this point in time, and this alone is not a fully developed DT but a preliminary stage towards its full development. The digital model has no connection between the digital and the physical object. After some work, the digital shadow emerges with a one way communication from the physical to the digital object.

In the MOL phase, the DT is concluded by also having the digital object exchanging data into the physical one, thus having a two way communication between objects. Despite the fact that companies may have large amounts of data, almost none is used/reused in the MOL phase processes to create (to evolve from the digital shadow) and maintain digital twins. This can mostly happen because of data silos or a wrong communication between the teams working in the BOL and MOL phases[25].

In the EOL phase, a product in the end of the life cycle prevents users from receiving updates since the company does not plan to continue updating the product, indicating that the product is at the end of its useful life (according to its vendor/distributor). In our context this phase is not important, since the designed prototype is still in the BOL phase.

2.2.4 Digital Twin Data

Early data gathering is predominantly a manual process in the high majority of projects, which can suffer from low efficiency and high monetary costs. The collected data may be inferior in quantity and quality for real-time performance, thus not being fully qualified for a long-time representation of a physical object. The usage of digital twins and other technologies (e.g, cloud computing and IoT) puts in place new requirements, such as:

- **Comprehensive data gathering –** Enhances the accuracy, efficiency, and adaptability of DT-based services. Data should be gathered from both physical and digital worlds reducing the existence of possible flaws.

- **Real-time data interaction –** Enables coordinated operations between the physical and virtual models. With data from the physical entity, the virtual models can be adjusted to the new received data, allowing updates to the simulation plans. Having the virtual model updated brings timely diagnosis and maintenance for the physical product.

- **Data universality –** Low universality of data is one of the main difficulties for DT applications. It can be hard to exchange data from multiple physical entities and achieve a smooth data integration because of different data formats.

- **Knowledge mining –** It is needed to retrieve knowledge from raw data through data mining, but it is not always possible since it is not an exact science and the raw data might be irrelevant or redundant to the already gathered data.

- **Data fusion –** Data from physical entities can be affected by sensor malfunctions and human interference. Data retrieved from virtual entities may also have abnormalities because of the used mathematical models. Data interference and gathering problems can reduce data reliability. Data fusion, data obtained from diversified sources is integrated synthetically, can solve some of these problems. When applying data fusion, data is verified and corrected assuring higher data consistency.

- **Iterative optimisation –** New obtained data is fused with the existing data, generating new valued information with each optimisation (new fusion).

- **Convenient data usage –** Different fields can have different data requirements. Field operators need operational data (e.g., assembly sequence) and managers require marketing data(e.g., material cost). Therefore, it is necessary to encapsulate data supply according to the needs of the current user.

Having the previous requirements on mind, a new notion was proposed, Digital Twin Data (DTD), which is data closely related to the DT[26]. In Figure 2.3, the composition of DTD is displayed from the requirements listed before.

Each requirement is assigned its respective principle enabling data gathering and its use in the most correct and efficient way. Just as there are requirements, there are also seven principles that are visible in the figure below. 2.4.

The seven principles mentioned before are:

- **Complementary principle –** It highlights the need of gathering data from physical and virtual objects. The physical product reflects uncertainty and complexity, which

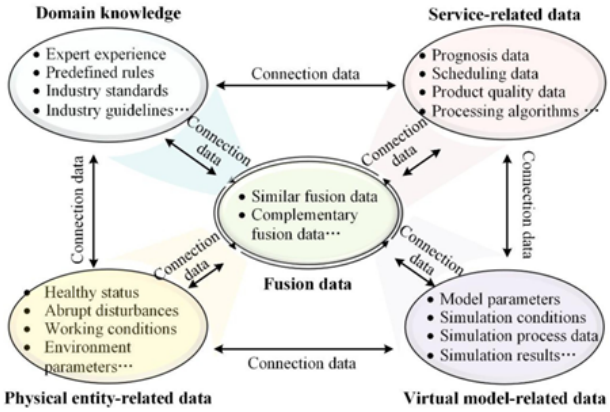


Figure 2.3: Composition of digital twin data [26].

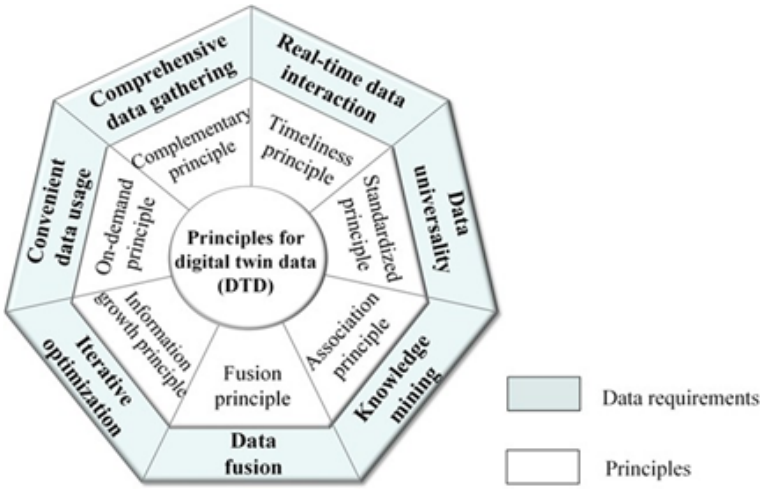


Figure 2.4: Principles for digital twin data [26]

are hard to simulate. Data obtained from the virtual object are rare event data and multi-physics simulation[15] at low cost.

- **Timeliness principle –** The data transfer between the two parts of the DTD should be adjusted to ensure a fast twinning process (data synchronisation). If the connection is discovered to be inconsistent it should activate a diagnose inconsistency and, if possible, restore consistency.

- **Standardized principle –** Data obtained from multiple sources, has to be standardised to a unified format and interface (visual representation). To achieve data universality a template listing the differences between the different formats and the standard one is needed.

- **Association principle –** Extract data from different parts of the DTD, like physical entity-related, virtual model-related and service-related data, to gather important information such as correlation of performances and dependency of data variables.

[15] https://plm.sw.siemens.com/en-US/simcenter/simulation-test/multiphysics-simulation/

- **Fusion principle –** Fusing analogous data from the physical and virtual objects minimises randomness and fuzziness of the physical entity data and can improve the reliability of the virtual entity data. Also more comprehensive data can be gathered increasing the information details.

- **Information growth principle –** The DTD should be improved using the data fusion principle and after each fusion follows an evaluation period whether to accept or reject the last fusion, keeping the data growth.

- **Servitization principle –** Data is encapsulated and treated as "black boxes" according to input, output and control mechanisms. When a user soughs access to certain data, it is decomposed into tinier requests where suitable services are searched, matched, and combined to get the solicited data. It allows the knowledge and skills of the user requesting the data to be lowered[26].

2.2.5 Digital Twins in Construction

This Section is important because gives the reader another case of how digital twins are used in other areas, and how we want to use some of those tools in future work. The flow of monitored data from the physical object to the digital processes is an essential part of digital twins. Before in construction, and also in other areas, most projects tracked the work progress by manual observation and measurements, but it was very time consuming and could lead to errors. To improve the field, many technological solutions for automatically monitoring construction work were proposed and tested, and some of them even became available to be applied commercially. Some of those technologies can be seen in table 2.1.

Technology	Hardware	Common Applications
Eletronic location and distance measurement	Robotic total stations, and range finders. Laser Scanning	Record current state of construction
Global Position System (GPS)	Differential GPS readers	Locate and measure work done; track production progress
Computer vision (stills and video)	Video, stills, 360° images	Safety; production progress; labor; and equipment
Audio and sonar	Microphones	Identify equipment function and use
Tag identification systems	Bluetooth Low Energy (BLE), radio-frequency identification (RFID), barcodes	Track materials; worker locations and durations; quantity and quality
Communication networks	Wi-Fi, ultra-wideband (UWB), cellular	Material tracking; worker locations and durations;safety
Smart sensors and sensor networks	Temperature, humidity, pressure, strain, rotation; IoT, edge computing	Monitor construction quality; monitor structural health; monitor safety

Table 2.1: Data acquisition technologies in construction[27].

In the built environment, the DT concept has been applied almost entirely to operational and maintenance project phases. BIM procedures are mainly used to define requirements and information in both operation and maintenance phases. Because of BIM "*most of the self-declared implementations of digital twins are limited to exploiting BIM as information stores and for visualizing information*"[27].

To improve digital twins in this area, two new approaches were suggested. The first one analysed digital twins in other areas and identified gaps that Construction Digital Twin (CDT) would try to solve. CDT is developed in three generations:

1. Enhanced version of the latest BIM.

2. Introduces semantics, where is deployed a web language framework to represent DT integration with IoT devices, being able to form a knowledge base.

3. The latest DT implementation is able to acquire knowledge using AI-enables agents, such as machine learning, deep learning and data mining. The AI technologies are needed to have a self-reliant, self-updatable and self-learning DT.

But there are limitations to the proposed CDT approach[27]. The first is that the formulation of a CDT starts with the conceptual assumption that CDT is a evolution/update of the BIM model. The second is the lack of a solid concept of the construction process. CDT is used as a technology to support the current practices in construction instead of being the main development method.

Due to such limitations the second approach was created[27], named Digital Twin Construction (DTC). DTC is a new methodology for managing production in construction that uses multiple site monitoring and AI technologies to provide accurate information. It makes possible to analyse and optimise the current design, planning and production. DTC also uses the BIM technology, combining it with the DT concept, AI and lean construction thinking, being able to create a centred data technique for construction management.

DTC operates with the acceptance that the real-time project information flow enables a closed loop model of construction, which could not be achieved before. The Plan-Do-Check-Act (PDCA) cycle supplies the indispensable process structure for the closed loop production control. The PDCA cycle and its correspondent DTC steps can be seen in Table 2.2. The main difference between DTC and other construction approaches is in the "Check" phase. If all data can be rigorously interpreted it can produce accurate and comprehensive information automatically in short periods of time. Such information when combined with the project BIM models can evaluate other product designs and product plans.

DTC has other potential benefits when applied correctly. In figure 2.5, it is possible to see on the left side the monitoring processes (boxes 1-3), in the middle (boxes 4-17) the causal links established in research[27] and the right side (boxes 18-23) are the expected benefits. Most of them are straightforward, but some might need extra clarification. In box 5, "Continuous learning" uses information of completed DT projects to plan and

PDCA	step	DTC step	Description
P	Plan	Model	Digital modelling of construction plans using BIM technologies
D	Do	Build	Manufacture and construction, on and off site
C	Check	Monitor and interpret	Digital monitoring of operations Intelligent interpretation of the monitored data generating product information and performance patterns
A	Act	Evaluate and improve	Evaluate product design Improve design and construction by making and applying actionable decisions

Table 2.2: DTC workflow applying PDCA cycle [27].

manage better products in the future. Box 9, "Reliable production planning" is achieved by scheduling only work that can be done safely in the first time.

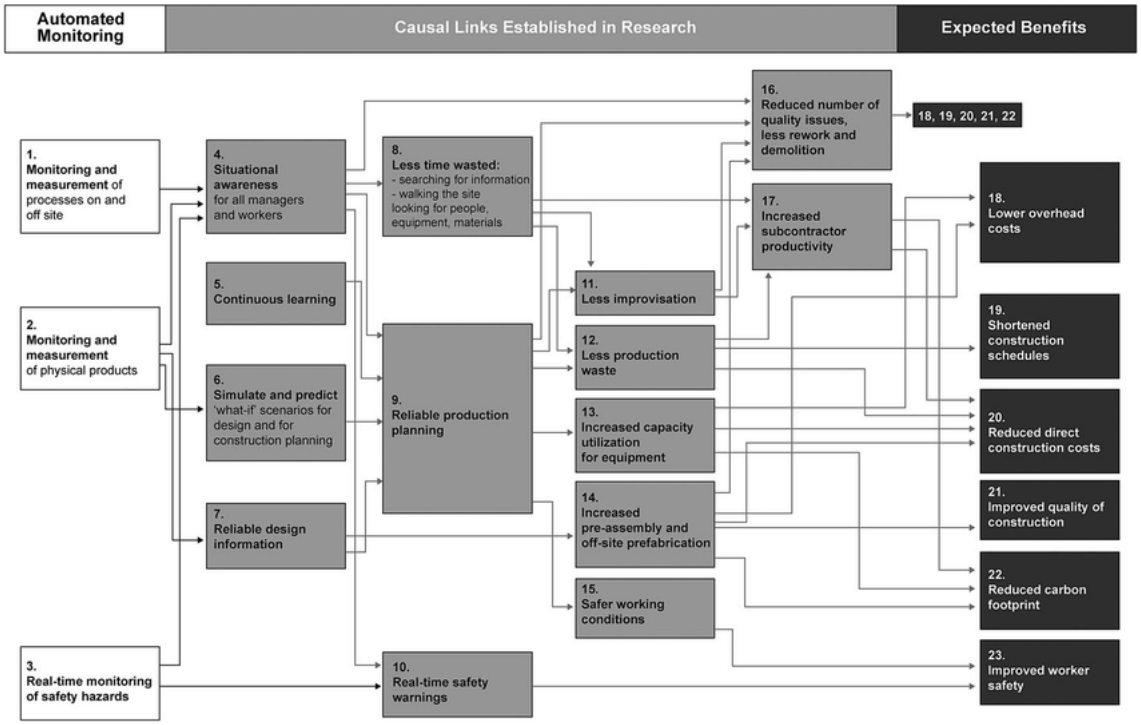


Figure 2.5: Digital Twin Construction improvements and expected benefits[27].

2.2.6 Digital Twin in Ships

Generally two main groups of applications exist when digital twins are implemented in the ship industry. The first group gives support for ship operations, focusing on condition monitoring and uses real operational data to calibrate simulation models.

There are already some applications of the first method, one of them helps to estimate the speed loss caused by marine fouling using neural networks (machine learning), where the network receives data from a vessel and returns the estimated speed loss. Since this method uses machine learning it needs large amounts of data[28]. Another application is a DT for ship motion and structural fatigue due to waves. Using weather forecast data for the ship route, the digital twin would be able to calculate an approximation of the caused

damages[29]. This second application uses specialised formulas not machine learning like the first one.

The second group includes digital twins used for system integration, as tools, and personnel training. One example is a system that can emulate system controls. This system has a detailed simulation model of the lay tower clamp in a pipe-laying vessel linked to controllers, always including hardware and a human in the loop system, used for hardware testing and operation training[30].

Most digital twin implementations in the ship industry still do not include extensive and integrated digital twins. Many are only used in early stages of development or to solve specific tasks and/or problems. DT functionalities to monitor and simulate ship behaviour are fairly recent unlike comprehensive ship representations. In attempts to separate the data obtained from digital twins three categories were created: 1) asset representation; 2) behavioural models; 3) measured data.

In Figure 2.6 it is possible to see the interaction of "measured data" to different digital services, with the digital twin acting as the central hub. The data must align so its interaction is done more efficiently, hence proving that the content of a service implementation depends on its domain[31].

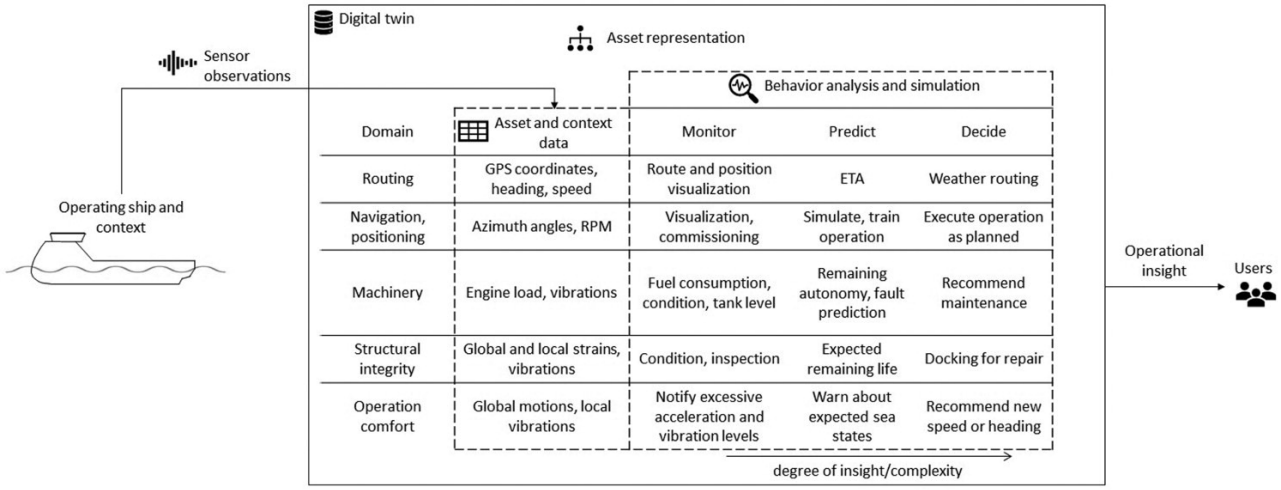


Figure 2.6: Digital twin elements and its usage[31].

2.3 Digital Heritage Metadata

In the last few years there has been an increase of national and international projects to develop interfaces for the common provision of metadata describing digital and non-digital cultural objects from different communities (archives, libraries, historic preservation organisations, museums, cultural science, etc). Some of the most distinguished projects

are Digital Library[16], WorldCat[17] and Europeana[18][12].

Since Europeana and Europeana Data Models will be mentioned in Subsection 2.3.1 a brief introduction is needed. Europeana was launched in November 2008 by the European Commission with the prototype European Digital Library Network (EDLnet). It is Europe's digital cultural platform and, currently, provides access to 58 million digitised cultural heritage collections (such as artefacts, music and sound files, and images of cultural heritage buildings) of more than 3600 cultural heritage institutions and organisations. Europeana allows for responsible, sustainable and innovative tourism, inspiring people to discover beautiful cities and landscapes, historic places and hidden gems across Europe[32].

Data models for heritage purposes are often designed based on the community requirements instead of addressing requirements for cross-community interoperability therefore, often, it is difficult to harmonize the metadata. For example, data models used by historic preservation and cultural science organisations are often domain-specific or in-house solutions, only partly compliant to internationally used metadata standards. In order to to shorten the gap between different models, some cross-community models are used, such as: Europeana Data Model (EDM) and Conceptual Reference Model (CRM), respectively explained in Subsection 2.3.1 and Subsection 2.3.2.

To address these difficulties in the digital heritage metadata field, the Dublin Core Metadata Initiative[19] (DCMI) created the Dublin Core Cultural Heritage Metadata Task Group[20]. The objective of the Task Group is to identify the challenges of metadata for cultural heritage and to provide a simple cross-community metadata model for Cultural Heritage Objects giving a recommendation, providing a basis for the development of DCMI Application Profiles. Some of the best and renowned applications based on Dublin Core are:

- Document type definition that is the Open Source Metadata Framework (OMF)[21]. OMF collects data about Open Source Documentation (metadata) that is used to describe the documentation. It acts as sophisticated card catalogue type of system for the metadata projects that exist;

- PBCore[22] is organised as a set of specified fields that can be used in database applications, and is also used as a data model for media cataloguing and asset management systems;

- Europeana Data Model (EDM), which is explained in Subsection 2.3.1.

[16] https://digitallibrary.io/
[17] https://www.worldcat.org/
[18] https://www.europeana.eu/en
[19] https://www.dublincore.org/
[20] https://www.dublincore.org/groups/cultural-heritage/
[21] https://www.ibiblio.org/catalog/items/show/3749
[22] https://pbcore.org/

2.3.1 Europeana Data Model

The Europeana Data Model (EDM) is a new approach towards structuring and representing data delivered to Europeana by the various contributing cultural heritage institutions. The model aims at greater expressivity and flexibility in comparison to the current Europeana Semantic Elements[23] (ESE), which it is destined to replace[33]. ESE is a flat model (one of its major problems) and metadata about the original object, its web representation and the aggregation are undifferentiated in the element set, unlike EDM that enforces the separation of data. The default mapping makes wide assumptions about where the data should go and these decisions are sub-optimal for any particular collection of data[34].

EDM is an interoperable framework that allows to collect, connect, and enrich cultural heritage metadata based on Dublin Core and Linked Open Data[24] technologies and has the following solutions over ESE:

- EDM transcends domain-specific metadata standards, yet accommodates the range and richness of community standards such as Lightweight Information Describing Objects[25] (LIDO) supporting the full range of descriptive information for museums objects, Encoded Archival Description[26] (EAD) encodeing descriptive information regarding archival records or Metadata Encoding and Transmission Standard[27] (METS), which encodes descriptive and structural metadata for digital libraries objects.

- It facilitates Europeana's participation in the Semantic Web, basing itself on an open, cross-domain, semantic web-based framework.

- EDM is a more developed data model that brings more meaningful links to Europe's cultural heritage data. Data from partners or external information resources will connect to other initiatives and institutions allowing to share enriched content, add to it and thereby generating more content in ways that no single provider could achieve alone.

- The EDM semantic approach will translate into the richer resource discovery and improved display of more complex data.

The EDM uses RDF(S)[28] as its meta-model and URIs[29] to identify structured information about cultural heritage objects. The structural modelling framework for the EDM ontology is provided by the Open Archives Initiative Object Reuse & Exchange (OAI-ORE)

[23] https://pro.europeana.eu/page/ese-documentation
[24] https://www.ontotext.com/knowledgehub/fundamentals/linked-data-linked-open-data/
[25] https://cidoc.mini.icom.museum/working-groups/lido/lido-overview/about-lido/what-is-lido/
[26] https://www.loc.gov/ead/EAD3taglib/EAD3.html
[27] https://www.loc.gov/standards/mets/METSOverview.v2.html
[28] https://www.w3.org/RDF/
[29] https://en.wikipedia.org/wiki/Uniform_Resource_Identifier

specifications[30]. This open architecture of the EDM makes Europeana compatible with the Semantic Web[31] paradigm and enables it to become part of the emerging Linked Open Data (LOD) community. In fact, the EDM provides a migration path for cultural heritage institutions from their currently mostly closed information architectures to open, linked environments for the benefit of both these institutions and the WWW community[33].

The LOD additionally offers a flexible and scalable way of building Digital Twins, since it offers a single interface to visualise and interact with all the collected data, either from the digital environment or the physical entity from this project or a set of similar projects. This way it simplifies the communication (sending messages and, if necessary, doing authentications) between all the systems (features) involved in the DT[35].

There are other innovations in the field, one of them is the Linked Conservation Data[32], which is a new project funded by the UK's Arts & Humanities Research Council[33] on Conservation Documentation. It has a network that improves the distribution of conservation records linking them to other resources, enables re-use and discovery, and increases everyone's knowledge by sharing observations and learning from each other's practice. By re-using conservation data, researchers can extract better conclusions because they have access to larger samples and material evidence from expert observations[36]. The network has two areas of focus which are vital for implementing linked data solutions:

- **Terminology** – Discussion to agree and name the types of records created;
- **Modelling** – Discussion on how to encode/store data so it reflects real-life observations, thus are well founded sources for research and engagement.

2.3.2 CIDOC Conceptual Reference Model

CIDOC and the CIDOC Documentation Standards Working Group[34] (DSWG) have engaged in the creation of a general data model for museums, with a particular focus on information interchange. After several years of efforts, in 1999, the first complete edition of CIDOC Conceptual Reference Model (CRM) was created and submitted for standardisation, becoming standard ISO 21127:2006 in 2006. CIDOC work would not stop after submitting CRM to the standardisation process, so in 2000 the CIDOC CRM Special Interest Group[35] was initiated, which is a volunteer community dedicated to the development and maintenance of a common standard for integrating cultural heritage data[37].

CRM is a theoretical and practical tool for information integration in the field of cultural heritage, the outcome of over 20 years of development and maintenance work, first standardised in 2006 and later renewed in 2014. It helps researchers, administrators and

[30] https://www.openarchives.org/ore/
[31] https://www.w3.org/standards/semanticweb/
[32] https://www.ligatus.org.uk/lcd/
[33] https://www.ukri.org/councils/ahrc/
[34] https://cidoc.mini.icom.museum/working-groups/documentation-standards/
[35] https://cidoc.mini.icom.museum/working-groups/crm-special-interest-group/

the public explore complex questions regarding our past across diverse and dispersed data sets. It can be achievable by providing definitions and a formal structure for describing the implicit and explicit concepts and relationships used in cultural heritage documentation and of general interest for the querying and exploration of such data.

CRM is developed in a manner that is intended to promote a shared understanding of cultural heritage information by providing a common and extensible semantic framework for evidence-based cultural heritage information integration. It is intended to be a common language for domain experts to formulate requirements for information systems and to serve as a guide for good practice of conceptual modelling. Is a living standard that is designed in such a way to provide both high level information retrieval and formulation as well as, documentation of very specific data points and questions[38].

2.4 Summary

This chapter presented some of the fundamental concepts, the basis of our work, in order to give the reader a better understanding of the topics discussed and analysed in the following chapters.

The chapter starts with the introduction to the concept of Digital Heritage explaining what it is, how and why it was originated but also referring why is so important in our lives. It also contains some basic notions about its preservation, presenting some techniques that are already being used in the field and some new potential ones that could help the faster growth of the digital heritage preservation.

The following section contains the concept of Digital Twin, making a detailed theoretical approach, since the next chapter contains some practical applications of it. The Digital Twin and its applications in the cultural and digital preservation are also presented, providing an insight to what will be built and accomplished in this dissertation. The concept of the IoT is explained, showing how useful it is to have all the systems linked in a vast network but also the problems and challenges that arrived with it, such as privacy and hacking issues. On top of that, contains a brief comparison between DT and IoT and how they can interact with each other.

The Digital Twin section also describes theoretical and practical research done in other areas, when gathering data to build a digital twin. First, are presented the life cycle phases in a product's life and how each phase has a different impact in the creation of the respective DT. There is also a theoretical approach on how to enhance the data gathering and finally two practical examples in construction and ships areas.

The Dublin Core Metadata Task Force is briefly described, its objectives and the importance of metadata when talking about digital heritage or digital preservation, showing two of the most used and renowned metadata models, the Europeana and CIDOC models.

Most of the previously discussed concepts only apply when a digital twin is in the process of creation or has already been developed. However, there are some concepts that have already been employed in this project to facilitate the future construction of the

digital twin. The concepts used include Product Life Cycle Phases, Section 2.2.3, some of the principles outlined in the Digital Twin Data section (Section 2.2.4), and adaptations of the Digital Heritage Metadata models (Section 2.3). These concepts are discussed in greater detail in the Solution Concept Chapter 4, in its initial section (Section 4.1).

3

Related Work

In this chapter, Section 3.1 presents available DT applications in different areas and also addresses the state of art of Digital Twin when applied to: Healthcare, Smart Cities and Manufacturing in Subsection 3.1.1 and in Immovable Heritage, Subsection 3.1.2. Examples of applications that use similar and relevant ways of implementing Digital Twin are also described in Subsection 3.1.3 and in Subsection 3.1.4. In Section 3.2, two examples of applications focused in preserving the artefacts heritage, similar to the application designed and developed in this thesis, are introduced.

3.1 Digital Twin Application in Different Areas

In this section, the state of art related to DT and its possible applications is presented, as can be seen in Section 3.1.1 and in Section 3.1.2. There are also some possible applications of DT in real heritage buildings and not only prototypes (or laboratory testings), see Section 3.1.3. Lastly, the last Section 3.1.4 contains an application of DT related to Web Services and Augmented Reality (AR).

3.1.1 Digital Twin State of Art in Different Areas

The vast growth of Digital Twin usage in the last years was facilitated by the availability of technologies like IoT and Big Data[1] and also the investment done in the area. These advances would not be possible without some key technological enablers like Artificial Intelligence (AI), IoT and Industrial Internet of Things (IIoT). In the already existing Digital Twin projects, most are small-scale, because there is a "*lack of domain knowledge on how to successfully scale up larger projects involving Digital Twins*"[39]. Most of the research, designing and implementation is focused on the manufacturing field, also existing some work in smart cities and healthcare. Fuller et al. concluded that in those latter two fields there are still a few gaps, when comparing to the manufacturing area, as can be seen in Figure 3.1. Below, the state of art of each of the areas mentioned above are quickly briefed.

[1] https://www.oracle.com/pt/big-data/what-is-big-data/

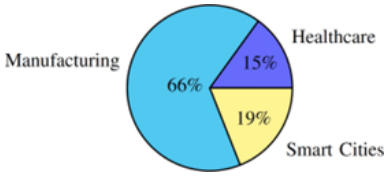


Figure 3.1: Percentage of research areas[39].

Healthcare

El Saddik redefined the industry with the inclusion of replications of living things as well as non-living entities, presenting potential to another sector other than the manufacturing one[40]. From a health perspective, the digital twin technology, when combined with AI algorithms[41], can be used to know the effects that specific lifestyle choices can have on a person's health and even recommend lifestyle changes, with AI and data analysis. It uses the full integration of both physical twin (human) and digital twin (replica), where it is possible to see that the impacts made to the replica would be the same to the person. The future of healthcare depends on combining cloud technology with digital twins to create a framework to monitor, diagnose, and predict the health of a patient[42].

Smart Cities

In recent years, research has seen substantial growth in urbanisation, when combined with the rise of IoT and data analytics[39]. There are some researches in urban planning and built environments, that have multiple uses. One of those is in the energy consumption field, promoting its use to monitor and compare energy consumption based on the environment and human impact. Another use could be to fuel the energy grid with the integration of renewable energy[43], for example wind power needs to be delivered, monitored, and analysed, which is an important challenge, since this needs to be extremely accurate. There are some other possibilities like to monitor livestock, a full sustainable farm[44] or even cars and traffic management[45]. For this to be achievable, there are still some obstacles like the challenge of data exchange which needs an improved connectivity in terms of continuity and as well as speed and quality since the better connectivity, the better accuracy of them.

Manufacturing

As previously mentioned, manufacturing represents more than 50% of the work and research in Digital Twin as stated in Figure 3.1. Manufacturing contains many sub-fields going from large smart factories to small machines/tools, and everything in between. Some examples of Digital Twin uses in the area are: simulation data fusion, interaction, and collaboration "as a service" that were made possible by enabling technologies, in particular IoT and data analytics[46], since all those collect the data using IoT embedded sensors, so after it can be analysed.

These various technologies when combined with DT, open a vast amount of opportunities to develop, taking advantage of each technology. For example, transfer learning[47]

can be used to find commonalities in algorithms to help create solutions that are transferable to other manufacturing processes. Then AI and machine learning[48] give enterprises the ability to test, simulate and optimise manufacturing processes in a virtual environment, ensuring increased quality and efficiency. According to Lu et al.[49], all energy spent in manufacturing needs to be monitored and reduced, so a potential solution for energy efficiency could be designed which would not only bring environmental benefits but also reduced costs, and increase in profit and investment.

3.1.2 Digital Twin Preventive Conservation of Real Estate Heritage

Recent decades have seen a shift in heritage conservation towards a preventive approach, emphasising the control phase to monitor evolving site conditions. This change reflects the growing recognition of maintenance's role in preserving significance, marking a paradigm shift in the field[2]. According to Heras Barros[50] preventive conservation takes advantage of systematic maintenance and regular observation of assets to "slow down the process of decay" and retain its cultural significance. "*Preventive conservation is based not only on assessment of state, but also on periodic assessments of risks and threats. By addressing deterioration causes and facilitating early damage detection, intervention is kept to a minimum*".

With the evolving interest around Cultural Heritage, some experts have begun to question how the preservation of heritage is approached and the necessity of basing decisions on the heritage place significance. The significance attributed to each place lies upon the interpretation of their tangible and intangible aspects, valuable judgement, and the prioritisation of some values by the involved stakeholders[51]. When dealing with the management of heritage assets, to be able to monitor changes, the stakeholders must access accurate and reliable information about the site's condition.

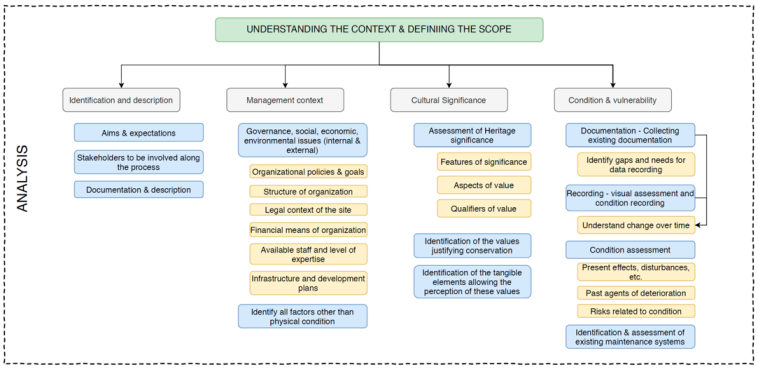
In the past, Building Information Modelling (BIM) was the most used process for heritage preservation, but in the last decade Historic Building Information Modelling (HBIM) has been introduced, a 3D parametric model of BIM. Additionally, there has been an increase use of DataBase Management Systems (DBMS) when using HBIM models, due to its high flexibility in data structuring as well as the interplay and relationships between the different data allowing stakeholders to extract key information by performing complex queries[52]. It was suggested that the next considerable challenge is to incorporate the Internet of Things as it spreads through the construction sector and can, eventually, bring advantages to support preventive conservation of immovable heritage. Besides DBMS and IoT, the subsequent use of 3D models as a digital replica in a Digital Twin environment may be used to monitor changes, detect risks, suggest possible solutions and assess the potential impact of both threats and interventions on significant elements carrying heritage values.

Jouan and Hallot[2] proposed a data model and a reasoning method that allows the integration of semantically enriched HBIM models in the DT environment to support

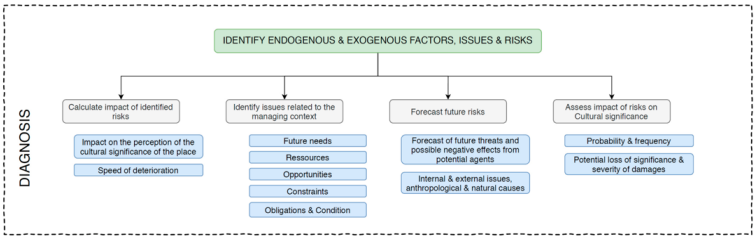
preventive conservation strategies. HBIM models, if adopting this method, would no longer be limited to the project phase as they would start to appear in the general management of heritage places, reducing the risk of becoming obsolete, and implying a better transmission of knowledge to future generations.

The automation of process analysis[53] in DT environment will spare resources in the long run and will increase the awareness of stakeholders on the potential impact of the conservation project they are supporting. There are four stages in this comprehensive method such as: (1) Analysis, (2) Diagnosis, (3) Therapy and (4) Control.

Analysis (1) wants to provide the stakeholders a good context of the site, its context and the management plan. Diagnosis (2) provides relevant and accurate information about all the found problems, also giving a basis answer on how to solve them. Therapy (3) intends to clarify the reasons for the management and conservation of the site. Lastly, Control (4) manages the implementation of the scheduled conservation activities and monitors the efficiency of the adopter solutions. These four stages are shown in detail in Figures 3.2 and 3.3.

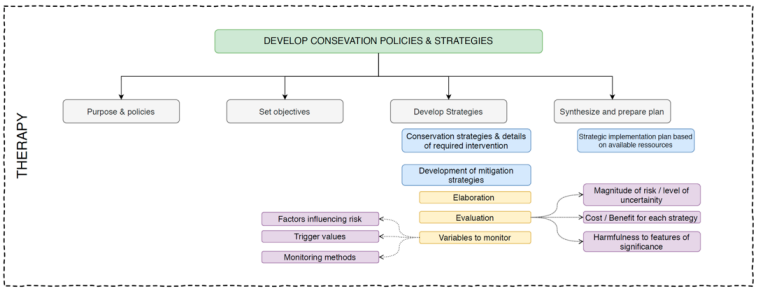


(a) Analysis Method

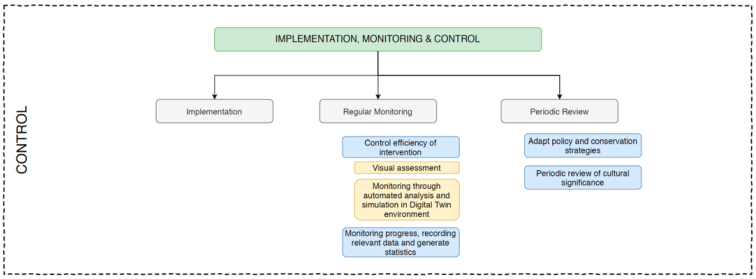


(b) Diagnosis Method

Figure 3.2: Analysis and Diagnosis Methods[14].



(a) Therapy Method



(b) Control Method

Figure 3.3: Therapy and Control Methods[14].

3.1.3 Application of Digital Twins in Infrastructure and Building Conservation

Currently, Digital Twin is mostly used in applications related to infrastructures and buildings, as was stated in Section 3.1.1. DT is very useful when combined with traditional techniques to have precise 3D and augmented reality (AR) visualisation of the buildings, not only to study how to improve the process of restoration but also as an amusement and tourism application as will be seen in section 3.1.3.1. It will also be possible to read about DT technology and how it can change people flow in a building in section 3.1.3.2.

3.1.3.1 Ballroom and the St. Francis of Assisi Church

The Pampulha Modern Ensemble (PME) is located in Belo Horizonte, Minas Gerais, Brazil. The PME was built around a lake, the Pampulha Lake, between 1942 and 1943 and led by the architect Oscar Niemeyer, landscaper Burle Marx, engineer Joaquim Cardozo and in collaboration with many other professionals. It is composed of the St. Francis of Assisi Church, the Casino (Pampulha Art Museum), the Ballroom (Centre of Reference in Urbanism, Architecture, and Design), and the Yacht Golf Club. The PME was declared, in July 2016, a UNESCO World Heritage Site since it is an outstanding example of modern architecture and has a high importance for Brazilian development architectural identity [54].

To be possible to have the real experience of visiting historical heritage sites without going there, Dezen-Kempter et al.[55] developed an AR mobile application for both the Ballroom and the St. Francis of Assisi Church. The application was built based on three steps as shown in Figure 3.4. The first step consisted on 1) collecting of spatial and documentary data, 2) data processing and 3) creating the HBIM model. In the second step the heritage elements were organised in the HBIM model using Dynamo[2] visual programming tool, creating building components groups so it would be easier to import to the AR system. The third step is the testing phase of the application, where users would do usability tests and give feedback to the programming team.

The HBIM is an application of the DT that includes a realistic representation of the buildings in a 3D model. It is also a tool that could manage all the data and models, crucially organising them so that it could support the development of the AR application.

After testing the application, the users highlighted the ease of accessing, with one click, the history of the building, the biography of the architect, and explore the components of the building (as if they were physically there) in an interactive way. At the same time they were able to see accurate 3D models and other extra architectural information. The use of DT and AR assists and promotes social interaction between architects, historians and visitors of historical heritage sites. These tools are, additionally, a cheaper way of investigating buildings, since unlike other subjects, a building cannot be studied in a laboratory.

[2] https://dynamobim.org/

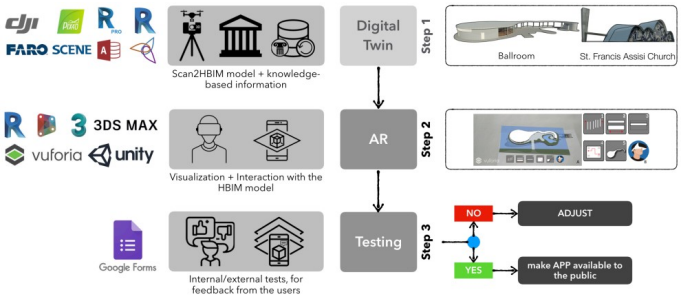


Figure 3.4: Roadmap from DT to AR creation[55].

3.1.3.2 Direct People Flow in Preserved Heritage Buildings

Palazzo della Civiltà Italiana, also known as Palazzo della Civiltà del Lavoro or in everyday speech Colosseo Quadrato ("Square Colosseum") is located in the EUR[3] district in Rome, Italy, a building of historical interest, protected by the Minister of Cultural Heritage. It was designed in 1938 by Giovanni Guerrini, Ernesto La Padula, and Mario Romano, and was built between 1938 and 1943, being inaugurated on November 30, 1940, despite being unfinished at the time. The building was never used for its true propose, which was to be the Museum of Italian Civilisation at the 1942 World Fair, demonstrating the superiority of Italian architecture. It was later revitalised as a business district and now is used by the Italian fashion house Fendi[4]. According to a legend, the structure's six vertical and nine horizontal arches correspond to the number of letters in the Italian dictator Benito Mussolini's name[56].

Heritage preservation buildings and museums have daily a great deal of pedestrian movement, so belt barriers and other solutions are used to redirect people. These solutions are optimal for safety and access but they are highly demanding in terms of people needed to manage them, and often they do not blend in completely with their surroundings, which can affect the perception of the displayed art[57].

The building is used by around one thousand people, every day simultaneously, because of its multiple purposes, which increases the hard job of controlling people flow when there are risky events or any safety/security threat. Besides that, there is the need to control the flow of all those people, when the building is opening or closing, and that can be seen in Figure 3.5.

Current solutions do not focus themselves on the building but on the people, and so are not optimal for heritage building preservation. Trento et al.[59] wanted to change that, so they designed and developed a prototype that focuses on the building and in the people. The system was created using an Agent-Based Simulation (ABS) on top of a HBIM receiving the data, which made it possible to create a DT of the building. This was possible by receiving data from physical sensors installed in the building (people flow) and the changes from the retractable barriers (controlling entering or leaving flow).

[3] https://en.wikipedia.org/wiki/EUR,_Rome
[4] https://www.fendi.com/pt-en/

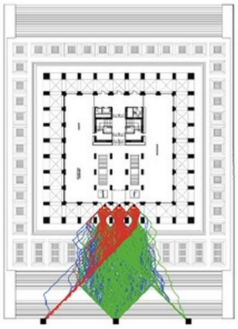


Figure 3.5: Exit flow of people of Palazzo della Civiltà Italiana[58].

Usually, in heritage buildings, the use of sensors, cameras and actuators is very limited since some problems may emerge: issues of heritage protection, privacy protection, ruggedness for use in outdoor environments or simply staff problems. On the other hand, a DT system offers the possibility to control people flow for increased security and safety, better space utilisation and a proper closing procedure[58]. These two approaches (DT and ABS) may seem contradictory but, when combined, most of the problems (like in this specified example) just disappear and one of the few remaining ones could be solved by adding a manual override to the system.

3.1.4 Digital Twin Applied to Web Services and Augmented Reality

With the fast-paced technology advancements, it is only logical that some of the work that was previously done by humans, has started to be done by machines doing the same exact work but faster and without compromising the final product. Most of those machines are controlled by some technological device or network, and since these networks are starting to get so very large, the management and handling of the data/information is becoming a challenge.

One of the key concepts proposed to overcome these challenges is Cyber Physical System[5] (CPS)[60]. A CPS is the integration of abstract computations and physical processes, where sensors and embedded devices are networked to sense, monitor, and control the physical world. The CPS links the cyber model to each device/machine (physical entity) that composes it so that they can be seen as the digital representation (Digital Twin) of the real entity, as it can be seen in Figure 3.6. The DT can monitor and control the physical entity, while each device sends data to its virtual model. The use of AR makes possible to see both the real environment as background and the virtual information in an interface, at the same time.

The integrated usage of CPS, DT and AR, allowed to design and create a system. The system implemented Web Services to retrieve data from the devices (into a data repository) and the AR system (client) provides an interface to visualise the data[62].

[5] https://www.rmit.edu.au/news/c4de/what-are-cyber-physical-systems

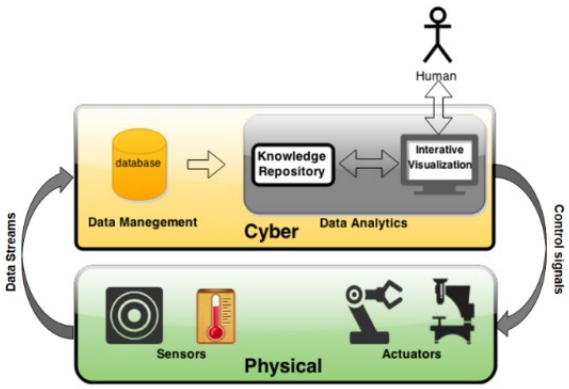


Figure 3.6: Architecture of a CPS system[61].

In this example, Schroeder et al.[61] built the application to visualise the extraction and initial process of oil and gas in an offshore oil platform. In the data repository, there were three tanks containing oil, water and gas that collected the value levels of each physical tank without using DT. If a DT of each tank were made it would also possible to retrieve more information such as: when the tanks were built, and real time data collected by the sensors. The middle service/layer was a normal web service application built in PHP[6] using Representational State Transfer (REST) and available from Apache[7] servers. The user layer (client) as previously explained, was the AR system where it was possible to see all the pictures and data updated in real-time. Users were able to easily access products and the manufacturing of data by a DT via browser, with the improvements to technological systems by using web services .

3.2 Work in Artefacts Heritage Preservation

After presenting the state of art of Digital Twin in several areas, this chapter presents work directly related to heritage preservation, more precisely, both to preserve paintings and their author's heritage. Section 3.2.1 contains a website that focus on general public, being highly interactive and, most of its data are vague (not exhaustively detailed) and are audio recordings. Section 3.2.2 presents a website little interactive as possible (users only have to search the information they are seeking) and the presented data are highly detailed essentially focusing on researchers and study teams.

3.2.1 Experience the Night Watch

Rijksmuseum, means national museum in Dutch, but when used independently, it refers to the Rijksmuseum in Amsterdam. The museum is located at the Museum Square in the borough of Amsterdam South, close to the Van Gogh Museum[8], the Stedelijk Museum

[6] https://www.php.net/
[7] https://www.apache.org/
[8] https://www.vangoghmuseum.nl/en

Amsterdam[9], and the Concertgebouw[10]. The Rijksmuseum[11] was founded in The Hague on 19th of November, 1798 and moved to Amsterdam in 1808 and is currently the largest art museum in the country[63].

In 2019, the Rijksmuseum, along with the NTR TV channel, a Dutch public-service broadcaster, celebrated the 350th anniversary of Rembrandt van Rijn[12] death, by hosting a series of major Rembrandt exhibitions, highlighting the master painter. Rembrandt's most famous painting, was painted in 1642 when he created an absolute masterpiece, the Nightwatch, an amazing painting "chock-a-block" (full of people) with secrets and stories[64].

This painting has such a great importance and magnificence in The Netherlands, that during the celebrations of Rembrandt, not only were hosted major exhibitions of the author, it was also created a website[13]. When we first enter the website we are presented by the painting, alongside with options and an audio introduction explaining its history[65], as can be seen below in Figure 3.7.

Figure 3.7: Night Watch First Options[65].

After concluding the introduction, or skipping it, the user can select one of the options, in this example "Composition" was selected. Right after selecting it, another audio introduction describes the people painted, as well, the light and how it can deceives the user when he is observing the painting. After listening to the audio, the user can select other options, as can be seen in Figure 3.8, with other audio recordings and the painting will automatically adjust to the specific spot being explained in the recording. This type of interactions (audio recordings and enlarged views of the painting) with the user are an important improvement in the area, since it does not only exhibits the painting alongside its extensive information, which is the usual presenting way.

[9] https://www.stedelijk.nl/en
[10] https://www.concertgebouw.nl/en/
[11] https://www.rijksmuseum.nl/en
[12] https://en.wikipedia.org/wiki/Rembrandt
[13] https://nightwatchexperience.com/en

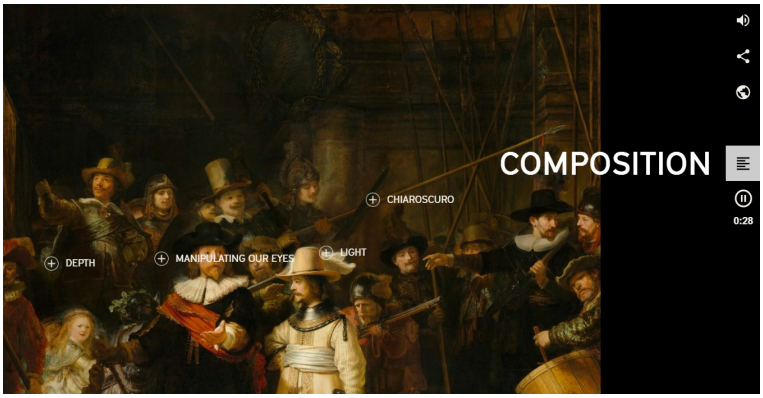


Figure 3.8: Night Watch with specific interactions and options[65].

3.2.2 Cranach Digital Archive

Considered the most successful German artist of his time, Lucas Cranach the Elder(1472 – 16 October 1553)[66] was a Renaissance painter and printmaker in woodcut and engraving. He was a court painter to the Electors of Saxony[14] most of his life, being known for his portraits of German princes and leaders of the Protestant Reformation[15]. Cranach also painted religious subjects, both in the Catholic tradition and in Lutheran religious, even painting nude subjects from mythology and religion. Cranach had 5 children, three daughters and two sons, both also artists as their father, Lucas Cranach the Younger and Hans Cranach.

Not much is known about Hans Cranach(1513-1537)[67], also known as Johann Lucas Cranach, besides being the oldest son of Lucas Cranach the Elder and being a German painter. Lucas Cranach the Younger(1515 – 1586)[68] was a more renowned painter and portraitist than his brother Hans. The Younger, after his father death, assumed full responsibility of the family workshop and although he was not a court painter, he worked for members of the social elite, including princes and nobles. In addition to the painting workshop, Cranach the Younger was a successful businessman and politician.

In October 2009 eight major museums in Europe and the United States began working together with the Kunstpalast[16] and the Fachhochschule Cologne[17] on a research project to provide access, in the electronic environment, to the paintings of an important protagonist of the German Renaissance: Lucas Cranach the Elder. The project is funded by the Andrew W. Mellon Foundation[18]. It is part of a larger initiative aimed at developing new research tools, designed to facilitate the transmission of historical art and conservation information across institutions and international borders. The ultimate goal is to advance scholarship and learning[69].

After starting this project in 2009, its third stage ended in 2019, where all their objectives

[14] https://en.wikipedia.org/wiki/Electorate_of_Saxony
[15] https://en.wikipedia.org/wiki/Reformation
[16] https://www.kunstpalast.de/en/home
[17] https://www.th-koeln.de/en/homepage_26.php
[18] https://mellon.org/

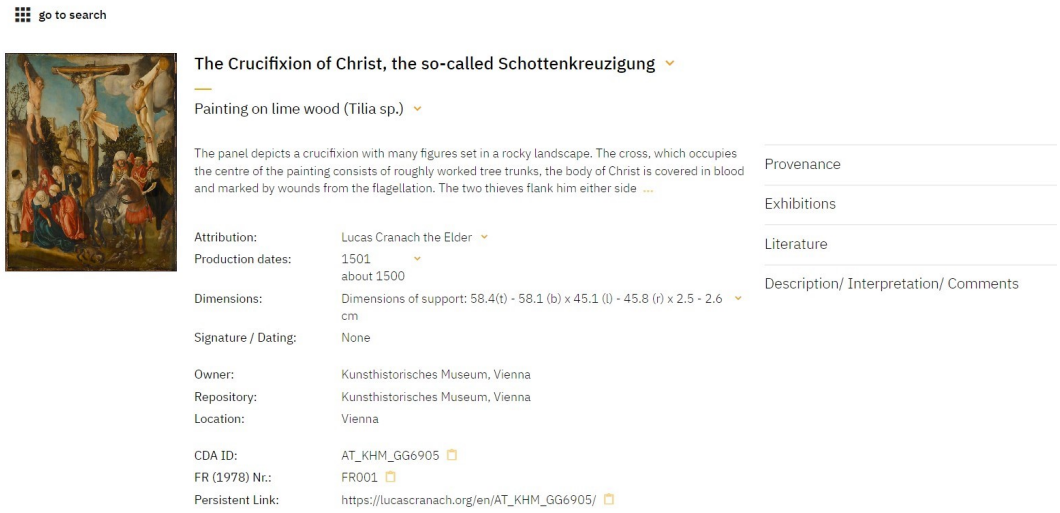


Figure 3.9: Public's options in the painting The Crucifixion of Christ in the Cranach website[69].

and expectations were met. During this time, a website[19], as can be seen in Figure 3.9[20] and Figure 3.10[21], was created to include all the paintings and information about: Cranach the Elder, Cranach the Young and Hans Cranach. Although, the general access area information is very accessible and easy to read, when it comes to the details and specifics about the paintings they could be organised in a different way, as can be seen in Figure 3.10.

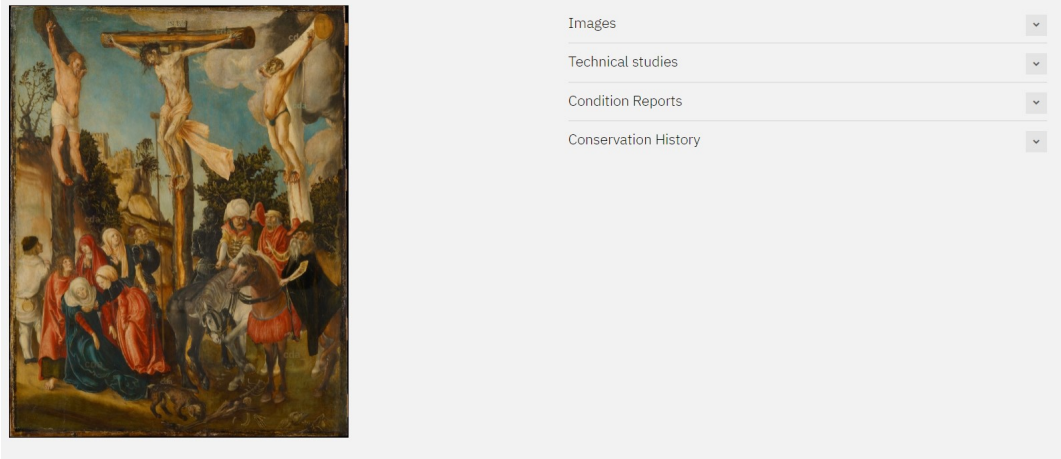


Figure 3.10: Researchers' options in the painting The Crucifixion of Christ in the Cranach website[69].

[19] https://lucascranach.org/
[20] https://lucascranach.org/en/AT_KHM_GG6905
[21] https://lucascranach.org/en/AT_KHM_GG6905

3.3 Summary

In the first section of this chapter, Section 3.1, some applications that are being used in other related areas like healthcare, infrastructure and buildings were presented.

First, in Section 3.1.1 a small state of art for digital twin in its different areas of application was introduced, which gives a small introduction to the following presented projects. Then, in Section 3.1.2 is presented how digital twin is used in preventive conservation of heritage infrastructures, just like we want to do in our work but applying the digital twin concept to art and artefacts.

Both Section 3.1.3.1 and Section 3.1.3.2 are related to Section 3.1.3 where two different applications using digital twin in infrastructures and buildings are shown. In Section 3.1.3.1 a digital twin of the Ballroom and the St. Francis of Assisi Church in Pampulha Modern Ensemble in Minas Gerais, Brazil, was created so users could appreciate and study the buildings from a remote location using their phone and AR technology. In Section 3.1.3.2, a digital twin of the Palazzo della Civiltà Italiana in Rome, Italy was also presented, with the intent of making the digital twin manage the flow of people automatically inside the building instead of it being done manually by someone. Both sections show practical examples of what is desired to be achieved not in the end of this thesis, but in future continuous work, the area of application being the main difference.

In Section 3.1.4 the use of digital twin to online web services is described, where instead of having multiple networks handling enormous amounts of data, that management is given to the digital twin. The application contains a database service, the digital twin and its "physical" counterpart, and an AR interface system where the information is presented to the user.

In Section 3.2 some examples of applications with interesting features similar to the solution proposed in future work, after the data gathering that was done in this dissertation, were presented. Both Section 3.2.1 and Section 3.2.2 are websites promoting digital heritage and digital heritage conservation, with two distinct ways of doing it. In the Night Watch Experience most data and information are explained via audio, not being very detailed and specific, where in the Cranach Digital Archive information is very thorough containing a variety of papers with information about colours, restorations and many other topics.

In the first, The Night Watch, the information presented is hard to assimilate and not very specific, in the second there is too much information and the organisation method does not enable data treatment for research purposes. So, combining the most useful features from these two websites as outlined in Section 4.2, we developed a prototype for an interactive application. We integrated it with the detailed information from the Cranach Archive, tailored to our own artifacts. This resulted in an interactive tool for manipulating and accessing/searching multiple data types associated to a single artefact in various ways.

4

Solution Concept

This chapter provides a comprehensive overview of the devised solution, tracing its evolution from the initial plan outlined in the dissertation proposal. It also outlines the solution's requirements, as detailed in Section 4.2, where both functional (Section 4.2.1) and non-functional requirements (Section 4.2.2) are explained. The chapter further showcases the initial prototypes that laid the foundation for the current design solution, available in Section 4.3. It encompasses an elucidation of the system architecture in Section 4.4 and an overview of the technologies employed, as presented in Section 4.4.1. To conclude, a concise summary of the entire chapter is provided.

4.1 Solution First Analysis

Before stating the system's requirements and architecture, it is essential to establish a connection between some of the digital twin details explained in Chapter 2 and their relevance to the solution. As previously explained, this dissertation exclusively deals with 2D images and representations of objects (artefacts). The developed application does not encompass or generate a digital twin of an artefact. Instead, this solution represents pioneering work by constructing a tool for initiating data input and its subsequent analysis. This approach establishes a comprehensive data structure, enabling the future digital twin development plans. The intended type is the "Asset Twins", as explained in Section 2.2. This choice aligns with the requirements to design and create a digital twin of an artefact as a whole, rather than focusing on specific components, as is the case with "Component Twins / Parts Twins".

Another important concept that merits attention is the Product Life Cycle Phases discussed in Section 2.2.3. Currently, this project is in the Beginning of Life (BOL) phase, where we are actively gathering the necessary data to create the initial digital model. This proactive approach sets the stage for a successful transition from the BOL phase, involving the transformation from a digital model to a digital shadow, to the Middle of Life (MOL). During the MOL phase, we can follow appropriate guidelines to enhance it even further.

In the Digital Twin Data (Section 2.2.4), seven requirements and principles were outlined. While most of these principles are only applicable when the digital twin already exists and cannot be used at this stage, it was chosen to implement the "standardized principle." This principle enables us to consolidate various data types, such as textual information and images from diverse sources, into a unified database for data gathering and a website for visual representation. Additionally, it was incorporated the "servitization principle," ensuring that all stored data is accessible for retrieval or management, with access varying based on the user's role in the system.

The last aspect to consider in this brief analysis is the type of metadata used in this solution. Initially, we discussed the Europeana Data Model in Section 2.3.1 and the CIDOC Conceptual Reference Model in Section 2.3.2. While both models include much of the required metadata for this project, there are certain data elements not covered by either model, including data regarding the equipment used to retrieve the artefact information, as one example. After outlining the project's requirements, which can be found in Section 4.2, and identifying the pertinent metadata for storage and usage in the application, we proceeded to adapt these two models to create a streamlined version that aligns with the specified metadata requirements. This adapted model aids in the organisation and management of metadata, as illustrated in the class diagram in Figure 4.4.

4.2 Solution Requirements

Taking into consideration the main objectives for the current dissertation, some requirements were brought up, including both functional, Section 4.2.1, and non-functional ones, Section 4.2.2, for the system implementation. Before listing the requirements a introduction to important concepts must be done:

- **Equipment —** Equipment encompasses all technological devices used to capture artwork or point information, which researchers deem important to include in the equipment information area,
- **Name Layer —** A name layer represents the spectroscopy process used to obtain the final point picture.
- **Point —** Enlarged point of a part of the artwork in which researchers have important information to analyse and study.

4.2.1 Functional Requirements

According to Visure Solutions[1] "A functional requirement is a statement of how a system must behave. It defines what the system should do in order to meet the user's needs or expectations. Functional requirements can be thought of as features that the user

[1] https://www.linkedin.com/company/visure-solutions/

detects."[70]. Their identification is a must if we want a complete and correct implementation according to the needs of VICARTE researchers, thus the following functional requirements were identified:

- **Insert and interact with diverse artwork information —** It is possible to insert, edit and delete all the information regarding an artwork, thus creating an accessible and robust collection of artworks. Additionally, it is possible to insert URLs[2] and PDF[3] that the researchers consider useful for the corresponding artwork.

- **Insert and interact with each zoom point —** It is possible to insert, edit and delete all the information regarding a zoom point. It is also possible to expand the available zoom point information by adding the equipment information used to retrieve the point data.

- **Search and filter artworks —** Since the main objective is to gather a large collection of artworks, it is needed a way to search and filter for specific pieces. At this point in time only name and layer type were discussed to be an option, but in future work the number of filters may increase.

- **Visualise all zoom points position filtered by spectroscopy analysis (layer) —** It is possible to visualise the zoom points location in the artwork filtered by each layer type, making it easier to identify each point to its corresponding image and information. Each layer is a different type of spectroscopy analysis used to retrieve information.

- **Visualise the artwork when different light frequency and transparency are applied —** Gives the possibility of changing the light frequency and transparency of the artwork image with a simple operation without changing the point location (if they exist in the selected layer).

4.2.2 Non-Functional Requirements

According to Scaled Agile[4] "Nonfunctional Requirements (NFRs) are intended to specify 'system qualities,' various systems attributes that are not directly related to their functionality. These attributes do not tell what the system does but how well it does it"[71]. The following non-functional requirements are the ones contemplated in the system:

- **Extensibility —** Since this dissertation creates the base support for the future digital twin, the system must be highly extensible, allowing easy updates to existing features, but also when creating new ones.

[2] https://pt.wikipedia.org/wiki/URL
[3] https://www.adobe.com/acrobat/about-adobe-pdf.html
[4] https://scaledagileframework.com/about/

- **Performance —** Execution of the system efficiently, mainly having into account the insertions and display of the added data.
- **Reliability —** It is important that the system is reliable, working as intended without experiencing failures or errors in the long run.
- **Portability —** The system must perform and be compatible in the most possible number of systems, in this case the most used and known browsers.

4.3 Prototypes

An initial prototype[5] was designed and created taking into account all the requirements that were brought up earlier in this chapter. This way it was possible to have an early discussion about the possible functionalities and design of the prototype, having some needed adjustments until the final product was developed. Every design and functionality update during the prototype phase and prototype testing took into account the initial system requirements.

The prototype was designed using a digital design platform named Marvel[6], where users can instantly download assets, generate CSS, Swift and Android XML code for their prototypes. Marvel is easy to use and has many components to choose from, making it easy for designers to create and share their designs.

In Figures 4.1 and 4.2, there are two examples of the very first design prototypes for the proposed application. In Figure 4.1 is represented the artwork gallery where the user can search from all the artworks in the system and be able to search for a specific one. This page does not have many differences from the final designed page, only a few details were changed or removed. In Figure 4.2 it is possible to see how the zoom of a specific point for a artwork would be displayed, but after some prototype testing it had to be redesigned, since it was not very logical and easy to use. Both figures represent a different functional requirement that were presented in Section 4.2.1. Their final designs and available operations, can be seen in Section 5, allowing for a better comparison with the initial ones.

4.4 System Architecture

In this section, the architecture of the developed system is presented, when combined with selected technologies, Section 4.4.1. The system architecture uses the 3-Tier Application Architecture (3-TIER) pattern design. According to IBM[7] "*Three-tier architecture is a well-established software application architecture that organizes applications into three logical and physical computing tiers: the presentation tier, or user interface; the application tier, where*

[5] https://medium.com/nyc-design/what-is-a-prototype-924ff9400cfd
[6] https://marvelapp.com/
[7] https://www.linkedin.com/company/ibm/

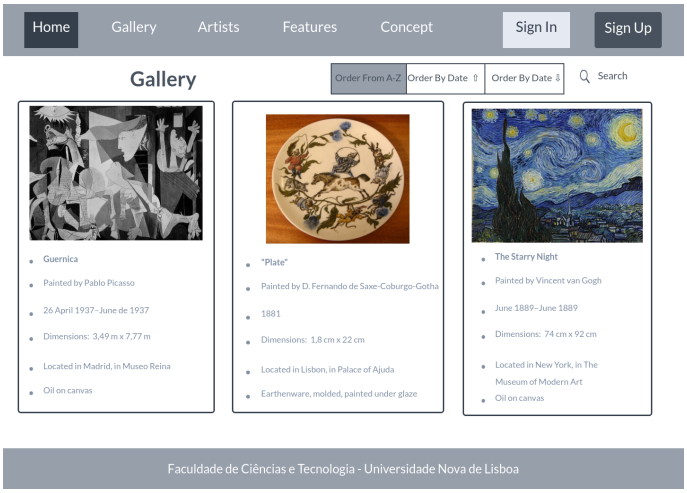


Figure 4.1: Artwork Gallery.

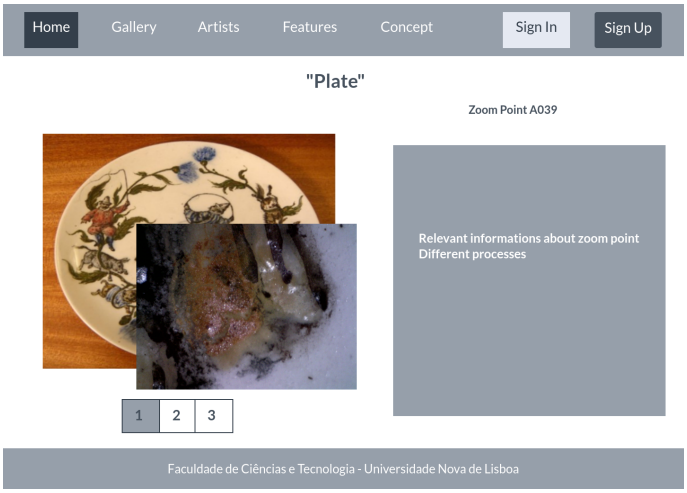


Figure 4.2: Zoom of a study point.

data is processed; and the data tier, where the data associated with the application is stored and managed."[72].

Having three separate layers brings multiple benefits, the main one being the separation of concerns[8] which allows multiple teams working at the same time in the same project, each one in their respective tier. Each tier is separate from the others and can be upgraded or scaled without affecting the other parts of the system. The system architecture diagram can be seen in Figure 4.3.

4.4.1 Technology Overview

In this section the technologies used in the implementation, Section 5, are presented and described thoroughly.

[8] https://en.wikipedia.org/wiki/Separation_of_concerns

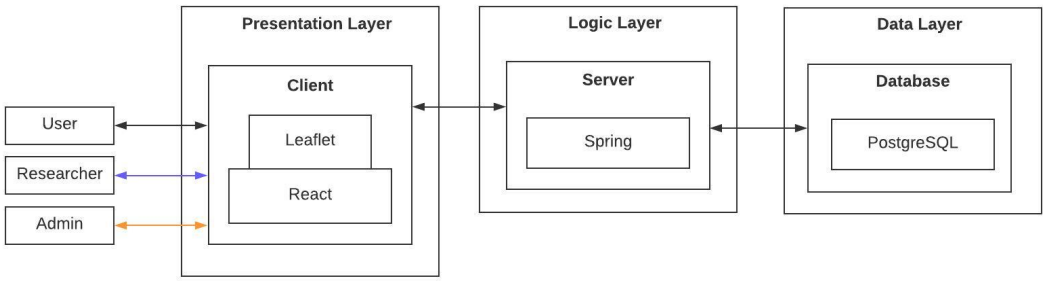


Figure 4.3: System architecture

Data Layer

The Data Layer contains all the infrastructure needed to store and organise all the available data, including the textual information and multimedia files like pictures. Since there was the need to organise the data and retrieve it when was needed a database was designed and created. The chosen database was, a Relational Database Management System (RDBMS), PostgreSQL[9] because there was the need to deal with large data sets, in which most of them could contain media files. "*PostgreSQL is the world's most advanced open source database and the fourth most popular database*"[73] and it is also highly extensible offering a wide variety of built-in PostgreSQL data types.

In Figure 4.4, it is possible to see how the data is organised, its corresponding data types and the dependencies between tables by using a Class Diagram[10]. For the development of the database it was mainly used pgAdmin[11], which is the most popular development platform for PostgreSQL, but also psql[12], a terminal-based front-end to PostgreSQL.

The class diagram has been updated since early project stages, which made a more streamlined and effortless way to create the respective tables and database for those in PostgreSQL (explained in detail in Section 5.1).

Logic Layer

The logical layer is responsible for the communication between the data layer and the presentation layer, letting the requested data from the database to be used by the web application. The logic layer is the server where all the logic is processed, from data insertion to data retrieving. It is implemented by the use of Spring Boot[13], "*an open-source tool that makes it easier to use Java-based frameworks to create microservices and web apps*"[74]. Spring is used since it gives the possibility to easily build a REST[14] (Representational State

[9] https://www.postgresql.org/
[10] https://www.visual-paradigm.com/guide/uml-unified-modeling-language/what-is-class-diagram/
[11] https://www.pgadmin.org/
[12] https://www.postgresql.org/docs/current/app-psql.html
[13] https://spring.io/projects/spring-boot
[14] https://www.codecademy.com/article/what-is-rest

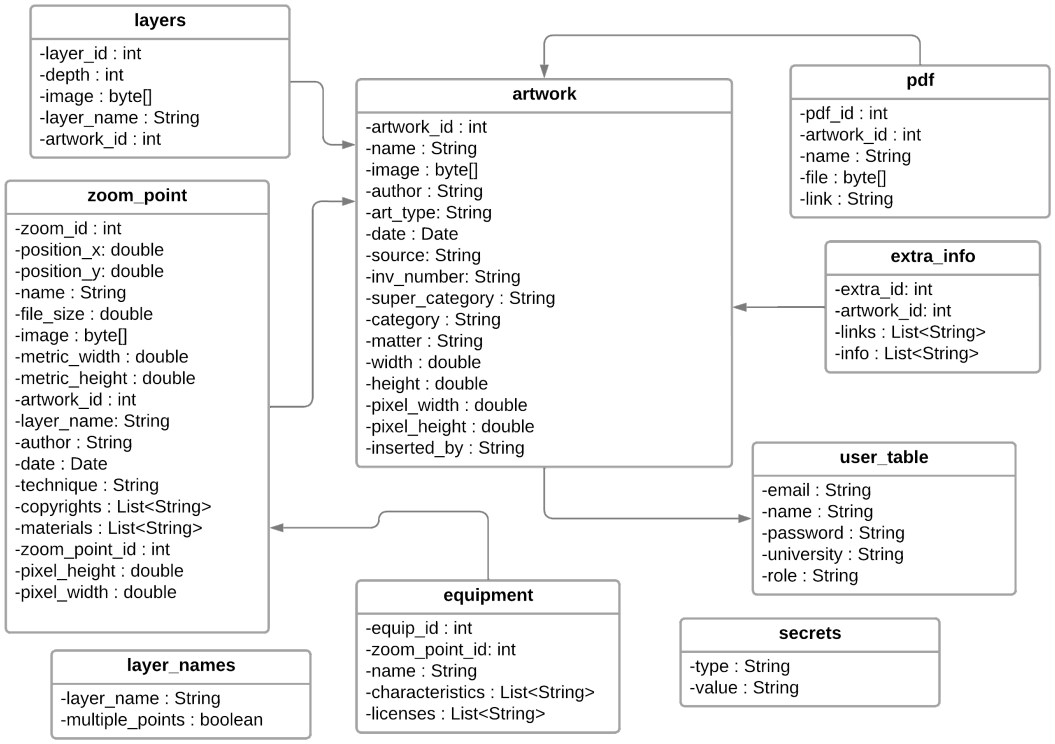


Figure 4.4: Class Diagram

Transfer) API[15] (Application Programming Interface).

The programming language used with Spring is Java[16], a highly flexible and user-friendly, being one of the most popular and widely used development languages in computing platforms for app development. It is also used Maven[17], a software project management and comprehension tool, that allows the developer to import needed dependencies for a better and robust development. There are two important dependencies, Hibernate[18] and Java Persistence API[19] (JPA). JPA is a Java specification for accessing, persisting, and managing data between Java classes and a relational database (in this case PostgreSQL), almost always without the need of creating Structured Query Language (SQL) queries.

Presentation Layer

The presentation layer is the web application developed, representing the technological infrastructure to support the user interaction with the data stored in the data layer. The web application was built using React[20], a free and open-source front-end JavaScript (JS)[21]

[15] https://aws.amazon.com/what-is/api/?nc1=h_ls
[16] https://www.java.com/en/
[17] https://maven.apache.org/
[18] https://hibernate.org/
[19] https://www.ibm.com/docs/en/was-liberty/nd?topic=overview-java-persistence-api-jpa
[20] https://react.dev/
[21] https://developer.mozilla.org/en-US/docs/Web/JavaScript

library developed by Jordan Walke[22], a software engineer at Facebook[23].

Developers using React can build user interfaces[24] (UI) based on components[25] that are connected to one another building the final HyperText Markup Language (HTML)[26] document[75]. React is still maintained by Meta (formerly known as Facebook) along with a community of companies and individual developers.

Although React is a JS library, it allows the users to chose between using JS or TypeScript (TS)[27], a strongly typed programming language that builds on JavaScript. TS applications usually have better code quality and understandability than JS[76], therefore it was the chosen programming language to develop in React. The implementation process is even made easier by the use of Typescript JSX(JavaScript Syntax Extension) files (TSX), which enables the use of HTML directly in the TS code.

It is also used the Leaflet[28] library for React, an open source JavaScript library used to build web mapping applications. It supports most mobile and desktop platforms, supporting HTML5 and CSS3. Among its users are FourSquare, Pinterest and Flickr[77]. Leaflet was adapted to this system, changing its main use as a mapping application, so some of its useful features like point location and non-geographical maps could be applied to our benefits.

4.5 Summary

This chapter has presented the development and the conceptual framework of the tool created specifically for this dissertation. Various sections of the chapter have discussed the tool's design and the technologies employed to bring it to fruition.

The chapter commenced with Section 4.1, which provided a brief analysis comparing the solution with the fundamental concepts introduced in Chapter 2. Following this, the solution's requirements, including both functional and non-functional aspects, were introduced in Section 4.2. Additionally, the evolution of the initial visual interfaces and features from the initial prototype to their current state, was elucidated in Section 4.3.

Lastly, the chapter delved into the system architecture (Section 4.4), explaining why this particular approach was chosen. The system was dissected into three distinct parts, and each was detailed in terms of its contribution to the overall system, along with the technologies used (Section 4.4.1).

[22] https://www.linkedin.com/in/jordan-walke-1250b634/
[23] https://about.meta.com/uk/metaverse
[24] https://www.techtarget.com/searchapparchitecture/definition/user-interface-UI
[25] https://react.dev/reference/react/Component
[26] https://developer.mozilla.org/en-US/docs/Web/HTML
[27] https://www.typescriptlang.org/
[28] https://leafletjs.com/

5

System Implementation

This chapter encompasses the implementation methods and offers illustrative examples of the designed features that have been integrated into the application. It comprises three substantial sections, each providing an exhaustive explanation of its respective components. In Section 5.1 the database's tables and data are elucidated, while in Section 5.2 the logic layer (server) design, organisation and implementation are presented. Finally, Section 5.3 provides detailed information about the design and implementation methods of the presentation layer (web platform).

This chapter delves into the implementation methods and offers concrete examples of the designed features that have been integrated into the application. It comprises three substantial sections, each providing an exhaustive explanation of its respective components. In Section 5.1, the database tables and data are elucidated, while Section 5.3 delves into the logic layer (server) design, organisation, and implementation.

Drawing upon the crucial information gathered to formulate the solution concept, as outlined in Chapter 4, we initiated the implementation of the designed solution. This implementation takes into account all the requirements raised, both functional and non-functional, as well as the valuable insights gained from the prototypes.

5.1 Data Layer - Database

First all data stored and used in this application should be explained before the features or even how the server can connect the database to the web platform. As previously indicated in Section 4.4.1, the data layer employs a RDBMS (Relational Database Management System), with PostgreSQL being the selected database system. The database serves as the framework in which all received data is systematically organized and stored. At present, there are nine tables within the database, each of which plays an indispensable role in maintaining the proper functionality of the application.

In Figure 5.1, we can observe how the data is structured, including the corresponding PostgreSQL data types, as well as the relationships between tables, as represented in

the Entity Relationship Diagram (ERD)[1]. To clarify further, the relationship between the "pdf" and "artwork" tables is such that multiple "pdf" objects can exist, but each of them corresponds to a single "artwork." Consequently, each "artwork" object can have multiple associated "pdf" objects.

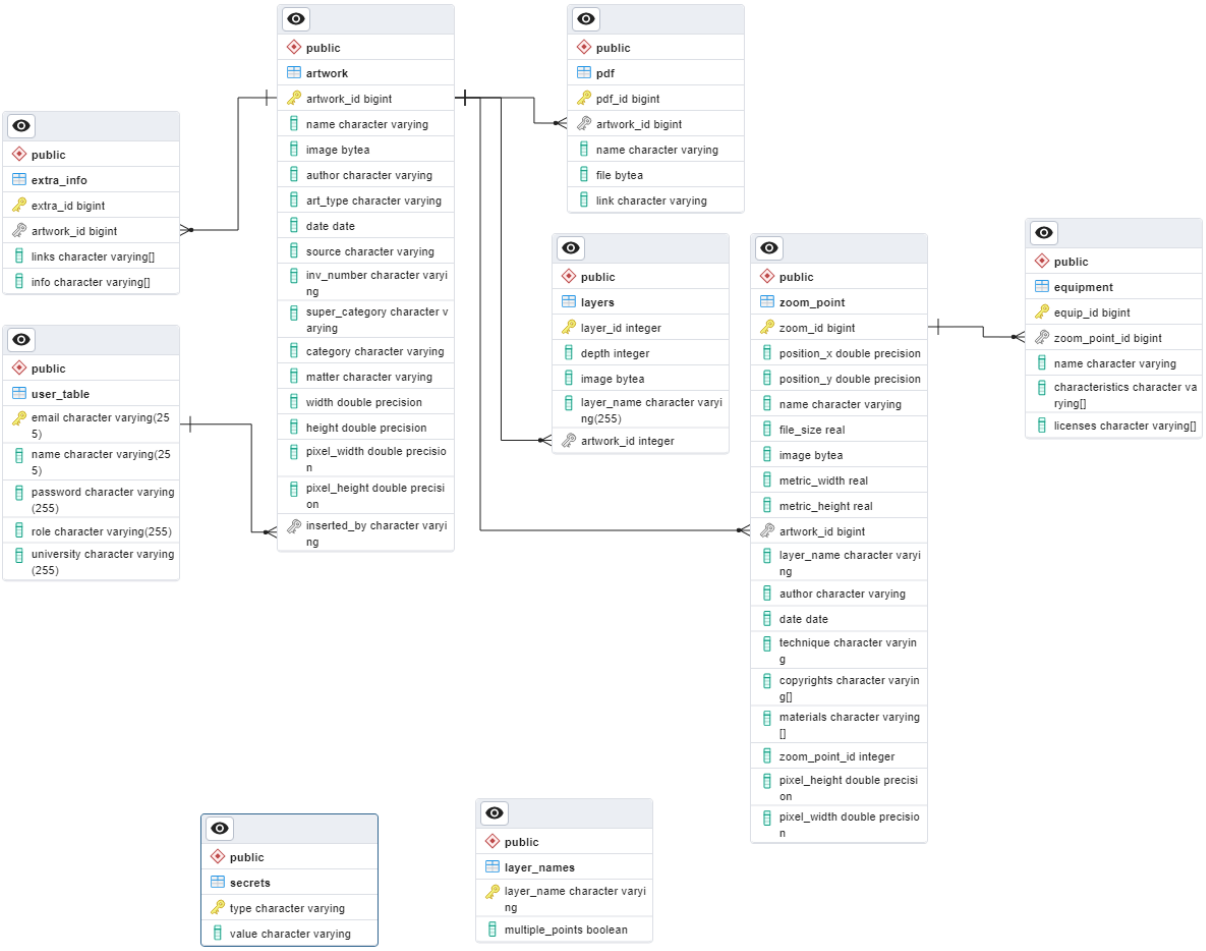


Figure 5.1: Entity Relationship Diagram.

Following some initial considerations about the database, its tables, and their relationships, it is imperative to gain an understanding of the data stored in each column of every table. In certain instances, the nature of the data (both type and value) contained within specific columns can be readily discerned based on their data type and column name. For instance, tables such as "artwork," "user_table," "zoom_point," "equipment," and "pdf" feature a column named "name," which serves as the label for the corresponding object (e.g., the artwork name provided by the creator, or the user's own name in the case of the "user_table" table).

User Table - user_table

[1] https://www.lucidchart.com/pages/er-diagrams

This table contains comprehensive information pertaining to the website users who have registered. Its primary purpose is to retain the email addresses registered within the system and define the role of each user on the platform. In subsequent developments, leveraging the uniqueness of each email address, new features such as group functionality or even a messaging system can be seamlessly incorporated. In the present deployment, each user is linked to an existing artwork (further elucidated in the artwork table section), with the user's role determining which features are accessible to the account logged into the platform.

Layer Names Table - layer_names

This table is dedicated to storing information about the layer to which artworks belong and whether these layers can accommodate points within them. Within the context of this work, various types of spectroscopic analyses (referred to as layers) are employed to analyse artworks. Some of these layers include XRF[2] and UV-Vis[3], which do not contain points within them. However, there is also the "Microscopy" layer, which can accommodate additional points as references. The utilisation of these layers and their respective points is elaborated upon in Section 5.3.

Secrets Table - secrets

This table stores essential tools required for back-office operations. Within this table, private and secure passwords are stored, enabling the deletion of system entities (e.g., artworks or zoom points) and the registration of accounts with elevated permissions in the system (such as higher roles like researcher or administrator). The passwords are encrypted using BCryptPasswordEncoder[4] with strength 10. Only users possessing the "admin" role (system administrators) have the authority to add new entries to the table or update existing values.

Artwork Table - artwork

The artwork table holds a paramount position within the system, as the existence of nearly every other table relies on it. As the table's name implies, it serves as the repository for artworks, encompassing their associated information and back-office data necessary to execute various functionalities. In Figure 5.1, the artwork table is depicted, complete with its columns, the majority of which are dedicated to artwork-related fields. For

[2] https://www.thermofisher.com/blog/ask-a-scientist/what-is-xrf-x-ray-fluorescence-and-how-does-it-work/

[3] https://www.technologynetworks.com/analysis/articles/uv-vis-spectroscopy-principle-strengths-and-limitations-and-applications-349865

[4] https://docs.spring.io/spring-security/site/docs/current/api/org/springframework/security/crypto/bcrypt/BCryptPasswordEncoder.html

instance, it includes columns for the artwork's name, author, date, inv_number (reflecting the artwork's physical storage location), category, width (measured in millimetres), and more. Two additional variables, "pixel_height" and "pixel_width," are stored solely for the purpose of defining the bounds (limits) for the Leaflet display, as elucidated earlier. The user responsible for inserting the artwork into the system is also recorded in the table, discernible through the "inserted_by" column.

In addition to the data stored in the tables, there are also two indexes[5] that have been previously established for this table, with the intention of utilising them in the future when the number of table entries reaches into the hundreds. Indexes play a crucial role in enhancing the database's ability to retrieve data swiftly from tables, provided they are created appropriately. The first index is tailored for the "inserted_by" column, while the second index is designed for the "name" (artwork name) column within the artwork table.

```
36  -- Index: idx_artwork_inserted_by
37
38  -- DROP INDEX IF EXISTS public.idx_artwork_inserted_by;
39
40  CREATE INDEX IF NOT EXISTS idx_artwork_inserted_by
41      ON public.artwork USING btree
42      (inserted_by COLLATE pg_catalog."default" ASC NULLS LAST)
43      TABLESPACE pg_default;
44  -- Index: idx_artwork_name
45
46  -- DROP INDEX IF EXISTS public.idx_artwork_name;
47
48  CREATE INDEX IF NOT EXISTS idx_artwork_name
49      ON public.artwork USING btree
50      (name COLLATE pg_catalog."default" ASC NULLS LAST)
51      TABLESPACE pg_default;
```

Figure 5.2: Indexes created for table artwork.

Pdf Table - pdf

This table stores Portable Document Format (PDF) files that researchers deem important for display alongside the artwork to which they are linked. There is no imposed limit on the number of PDF files that can be associated with each artwork. However, there is a size constraint for individual files, currently set at 10MB. Should a PDF file exceed this size, users have the option to upload it elsewhere and simply provide the corresponding URL. This approach prevents the database from becoming overloaded with large PDF files, which could potentially impact database efficiency in the future.

Extra Information Table - extra_info

[5] https://medium.com/geekculture/indexing-in-postgres-db-4cf502ce1b4e

The table for additional information closely resembles the previous one; however, it serves as a repository for additional links or URLs to external articles, images, or other pertinent information that researchers believe would be valuable to include. Furthermore, this table has the capacity to store various other types of information, including keywords that can be used as additional filters in the gallery's artwork filtering system.

Layers Table - layers

This table enables the storage of images with varying light levels or transparency applied to the "default" picture of an artwork. Each entry within this table includes the picture's name, its depth (e.g., where the default is 0 and others can be assigned values like 1), and the image itself. Each layer is associated with a single artwork, but an artwork can accommodate multiple layers. This table is instrumental in facilitating the functionality to change the background image of an artwork, as will be explained in the presentation layer section.

Zoom Points Table - zoom_point

This table serves as the repository for all zoom points and their associated information. It closely resembles the artwork table, with most of its columns dedicated to essential data about the individual points. However, there are other columns of significant importance that were employed using other tools, particularly Leaflet, to ensure that all data can be displayed as demonstrated previously.

Four columns within this table play a crucial role in this regard. "pixel_height" and "pixel_width," much like in the artwork table, determine the maximum bounds for an image background and are utilised exclusively for "special" points that can accommodate other points. The remaining two variables, "position_x" and "position_y," denote the point's location using the XY axis coordinates. These features are demonstrated visually in the functionalities depicted above in Section 5.3.

Similar to the artwork table, an index is also present in this table for the "layer_name" column. This index is particularly valuable for queries that involve filtering zoom points based on their respective layers.

```
39 -- Index: idx_zoom_point_layer
40
41 -- DROP INDEX IF EXISTS public.idx_zoom_point_layer;
42
43 CREATE INDEX IF NOT EXISTS idx_zoom_point_layer
44     ON public.zoom_point USING btree
45     (layer_name COLLATE pg_catalog."default" ASC NULLS LAST)
46     TABLESPACE pg_default;
```

Figure 5.3: Index created for table zoom_point.

Equipment Table - equipment

The equipment employed to collect data, information, or images that contribute to the creation of a new zoom point for a specific artwork is recorded in this table. Information such as the equipment's name, relevant characteristics, and any required licenses for its usage are stored. Each piece of equipment is linked to a single zoom point, although a zoom point may encompass multiple pieces of equipment.

5.2 Logic Layer - Server

As previously mentioned in Section 4.4.1 in the Logic Layer part, the server is implemented using Maven, the Spring Boot framework and programming language Java to build a RESTful API.

First, a new Spring Boot project using Maven was created using Spring Initializr[6], an official website tool from Spring designed to facilitate the creation of an empty project, which can be deployed or used for coding immediately. Then, all the dependencies needed to build the application in the POM file were added, which allows the use of different Java libraries to make the implementation more robust and easier. Afterwards, important properties were included in the properties file (Figure 5.4).

```
spring.servlet.multipart.max-file-size=10MB
spring.datasource.url= jdbc:postgresql://localhost:5432/thesis_db
spring.datasource.username= postgres
spring.datasource.password= [redacted]

spring.jpa.properties.hibernate.jdbc.lob.non_contextual_creation= true
spring.jpa.properties.hibernate.dialect= org.hibernate.dialect.PostgreSQLDialect

# Hibernate ddl auto (create, create-drop, validate, update)
spring.jpa.hibernate.ddl-auto= update
```

Figure 5.4: Properties File.

Some of these properties are required to establish a connection to the database (the password is crossed out for obvious security reasons) and specify which SQL language is being used (in this case, PostgreSQL). The first property sets the maximum file size that can be inserted into the database, which is 10MB. The last property in the file specifies how the database should behave. Selecting the "update" option means that it will update the database schema if any changes are made in the Data Transfer Objects (DTO) classes[7].

After the initial project setup and considering the class diagram designed for the system (Figure 4.4), the DTO classes were created. These DTO classes streamline the transfer of data between the presentation and data layers, simplifying method calls when updating

[6] https://start.spring.io/
[7] https://www.baeldung.com/java-dto-pattern

existing data. Figure 5.5 provides a glimpse of the UserDTO class. All the annotations mentioned in picture are provided by the JPA (Java Persistence API) dependency added to the POM file, as explained in Section 4.4.1. A DTO class exists for each class presented in the class diagram.

```
@Entity
@Table(name = "user_table")
public class UserDTO {

    6 usages
    @Id
    @Column(name = "email", nullable = false)
    private String email;
    6 usages
    @Column(name = "name", nullable = false)
    private String name;
    6 usages
    @Column(name = "password", nullable = false)
    private String password;
    5 usages
    @Column(name = "university", nullable = false)
    private String university;
    6 usages
    @Column(name = "role", nullable = false)
    private String role;
    3 usages
    @Transient
    private String newPw;
    2 usages
    @Transient
    private String newRole;

    1 usage  new *
    public UserDTO(String email, String name, String password, String university, String role) {
        this.email = email;        this.name = name;        this.password = password;
        this.university = university;        this.role = role;
    }
```

Figure 5.5: Some Content of the UserDTO Class.

The "@Entity" annotation specifies that the class represents an entity (object) and is intended to be mapped to a database table, while the "@Table" annotation designates the name of the corresponding table. Furthermore, all table columns are defined with their respective names in the database, as exemplified by the annotation "@Column(name = "email")," along with indications of whether they can be null[8] or not. Considering that the email field is designated as the desired primary key[9] for this table, it is imperative that the "email" field also be annotated with "@Id." Additionally, within the class, there are two variables bearing the "@Transient"[10] annotation. This annotation explicitly specifies that these variables are not intended for persistence in the database, signifying that they should not be included in the database table.

In order to establish a straightforward and seamless connection between the database

[8] https://www.upwork.com/resources/what-is-null-in-java
[9] https://www.tutorialspoint.com/sql/sql-primary-key.htm
[10] https://docs.oracle.com/javaee/5/api/javax/persistence/Transient.html

and the data, it is essential to create an interface[11] repository for each of the DTO classes. In Figure 5.6, it is possible to observe the repository designed for the ArtworkDTO class. The ArtworkRepository interface extends JpaRepository, which is another functionality provided by the JPA dependency.

```
public interface ArtworkRepository extends JpaRepository<ArtworkDTO, Integer> {

    1 usage  new *
    List<ArtworkDTO> findAllByOrderByIdAsc();
    1 usage  new *
    List<ArtworkDTO> findByName(String name);

    1 usage  new *
    List<ArtworkDTO> findByInsertedBy(String email);
}
```

Figure 5.6: Artwork Repository Interface.

In this example, the JpaRepository contains objects of the class ArtworkDTO and the id (primary key in SQL terms) is of type Integer. In addition, the interface encompasses three queries designed to retrieve data from the database, benefiting from the advantages of JPA, thereby eliminating the need to write SQL code to formulate these queries. The first query performs a comprehensive search of the entire artwork table and returns all objects in ascending order. The remaining two queries target specific columns (name and insertedBy) within the table for retrieval.

After the creation of the DTO class and the repository, we can commence the development of API calls for our application. Each API request[12] serves as the conduit for data flow between the database and the website, facilitating bidirectional communication. In Figure 5.7, a segment of the ArtworkController class is depicted. Additionally, a controller class exists for each DTO class. All the annotations featured in the figure are sourced from the Spring Boot libraries.

At the top of the class, we find the "@RestController" annotation, which designates this class as a request handler responsible for receiving requests from external sources. The RestController represents an enhancement over the "@Controller" annotation, consolidating both the "@Controller" and "@ResponseBody" functionalities (used for returning objects in the HttpResponse) into a single, comprehensive global annotation[13]. It's worth noting that controller classes should not contain business logic themselves. Their primary role is to facilitate the passage of data to service classes, fostering a clearer and more straightforward separation between the logic and HTTP handling responsibilities.

The "@RequestMapping" annotation is employed to associate HTTP requests with this specific class and its methods. The "g" variable, which utilizes the Gson library, serves to convert Java Objects into their JavaScript Object Notation (JSON) representation.

[11] https://docs.oracle.com/javase/tutorial/java/concepts/interface.html
[12] https://www.cloudflare.com/learning/security/api/what-is-api-call/
[13] https://www.baeldung.com/spring-controller-vs-restcontroller

```java
@RestController
@RequestMapping("/artwork")
public class ArtworkController {

    8 usages
    @Autowired
     private ArtworkService artworkService;

    2 usages
    static final Gson g = new Gson();

    pm-franco *
    @PostMapping(path = "/")
    public ResponseEntity<String> postArtwork(@RequestParam("file") MultipartFile file,
                                              @RequestParam("json") String jsonObject) {
        ArtworkDTO artwork = g.fromJson(jsonObject, ArtworkDTO.class);
        return artworkService.postArtwork(file, artwork);
    }
```

Figure 5.7: Artwork Controller Class.

Next, there's the "postArtwork" method, featuring the "@PostMapping" annotation, which maps HTTP POST[14] requests to particular methods. This method receives both a file and the artwork information encapsulated within a JSON object, which Gson subsequently translates into an object of the ArtworkDTO class. This object is then utilized by the artworkService class.

In Figure 5.8, we can observe the logic implemented in the "postArtwork" method within the ArtworkService, which receives its input from the ArtworkController class. The initial lines of code, up to the "try" statement, serve as data validators to ascertain whether the received data aligns with expectations and complies with the specified requirements. If no errors or issues are detected with the received data within the "try" block, the object (artwork) is subsequently saved in the ArtworkRepository. This action triggers an automatic insertion of the object into the corresponding database table.

```java
public ResponseEntity<String> postArtwork(MultipartFile file, ArtworkDTO artwork) {
    if (file == null || file.isEmpty())
        return ResponseEntity.badRequest().body("File can't be null.");

    if (checkInfo(artwork))
        return ResponseEntity.badRequest().body("Some required information is null or empty.");

    ResponseEntity response = userService.checkRole(artwork.getInsertedBy());
    if (response.getStatusCodeValue() == 400)
        return response;

    try {
        artwork.setImage(file.getBytes());
        artworkRepository.save(artwork);
        return ResponseEntity.status(201).body("Artwork created with name: " + artwork.getName());
    } catch (Exception e) {
        return ResponseEntity.badRequest().body(e.getMessage());
    }
}
```

Figure 5.8: Artwork Service Class Insert Artwork.

[14] https://developer.mozilla.org/en-US/docs/Web/HTTP/Methods/POST

5.3 Presentation Layer - Web Platform

In this section are presented the visual representation of the designed pages and features for the system, along with providing code insights into some of these operations.

5.3.1 Main System Operations

The next features, like the back-office ones (Section 5.3.2, are mostly set to be only used by qualified personnel (researchers, PhD students, etc...), since most of the work is very specialised and we have to guarantee the correctness and veracity of the stated information.

There is two big categories of presented information, the first one is Artworks. Artworks can vary from paintings, to enamels to sculptures and they are the main objective of this work. The main focus of the implemented system is to be able to gather all important information related to artworks so the research team and general public can access those details. The second category is Points, which were previously explained as enlarged points of a part of the artwork in which researchers have important information to analyse and study.

5.3.1.1 Artworks

In this section, we introduce the first feature: artwork insertion into the system. The process is illustrated in Figure 5.9. To add a piece of art, users must complete all the fields marked with a red asterisk, as they contain mandatory information. Users have the flexibility to begin by either entering the text information or uploading the image file. However, both tasks need to be completed before the "Create Artwork" button becomes clickable. The change in the button's background colour, from black to white, serves as an indicator that all mandatory information has been provided, signifying that the artwork is ready for insertion into the system repository.

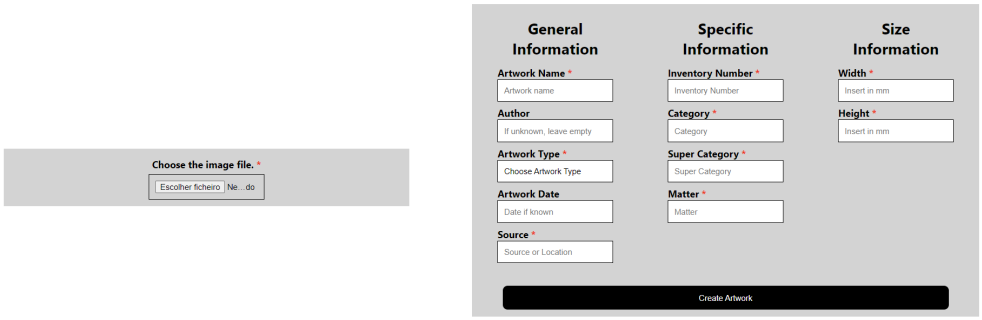


Figure 5.9: Insert artwork page.

In Figure 5.10, the code responsible for selecting and viewing artwork/point pictures is displayed. Within the code, we first accept input image files in PNG and JPEG formats and load the selected image. While the image is loading, crucial data is transmitted through the "props.handleSize(img.width, img.height, image)" operation. This operation enables

```
<div className={"imagem"}>
    <label className={"required"}>Choose the image file.</label>
    <input type="file" accept="image/png, image/jpeg" onChange={(e ...) => {
        const ev = e.currentTarget.files;
        if (ev) {
            if (ev.length === 0) {
                return;
            }
            var img: HTMLImageElement;
            img = document.createElement( tagName: "img");
            // @ts-ignore
            var image = e.target.files[0];
            img.onload = function () {
                props.handleSize(img.width, img.height, image);
            };
            img.src = URL.createObjectURL(image);
            // @ts-ignore
            setSelectedImage(image);
            setImgProp( value: undefined);
        }
    }}
    />
    {selectedImage && (
        <div className={"preview"}>
            <div>
                {imgProp?<img src={'' + selectedImage}></img>:
                    <img src={URL.createObjectURL(selectedImage)} alt={""}></img>}
            </div>
            <button onClick={removeSelectedImage}>
                Remove This Image
            </button>
        </div>
```

Figure 5.10: Insert figures to the system.

us to store the image's width, height, and the image itself in the system for future use with Leaflet. If the image is loaded successfully (unless there are issues with the picture itself), a button will appear, allowing the user to remove the current picture. Alternatively, the user can upload another picture, which will automatically update the display.

To facilitate the search and filtering of all artworks within the system, we designed and developed a gallery. In this gallery, users can search by artwork's name, filter by artwork's type, or employ both methods simultaneously for a comprehensive artwork search.The code for the filter and search features is displayed below in Figures 5.11 and 5.12, respectively. The "filterRows" function receives the rows (all artworks stored in the database), the filter (typing search filter), and filterSelect to filter through the different possible layers. The function accommodates four available scenarios, including cases where both filters are not assigned, one is being used and the other not, and the last case where both are active.

```
function filterRows(rows: any, filter: any, filterSelect: any) {
    if ((!filter || filter.length === 0) && (!filterSelect || filterSelect.length === 0)) return rows

    if (filter && !filterSelect) { return rows.filter((row: any) => {
            return (row.name.toLowerCase()).includes(filter.toLowerCase()) })
    }
    if (filterSelect && !filter) { return rows.filter((row: any) => {
            return (row.artType.toLowerCase()).includes(filterSelect.toLowerCase()) })
    }
    if (filterSelect && filter) { return rows.filter((row: any) => {
            return (row.artType.toLowerCase()).includes(filterSelect.toLowerCase())
                && (row.name.toLowerCase()).includes(filter.toLowerCase()) })
    }
}
```

Figure 5.11: Filtering data retrieved.

```
const handleSearch = (value: any, type: any) => {
    setActivePage( value: 1)

    if (type === "input") {
        if (value) {
            setFilter(value);
        } else
            // @ts-ignore
            setFilter();
    }
    if (type === "select") {
        if (value && value !== "default")
            setFilterSelect(value);
        else
            // @ts-ignore
            setFilterSelect();
    }
}
```

Figure 5.12: Handle searches.

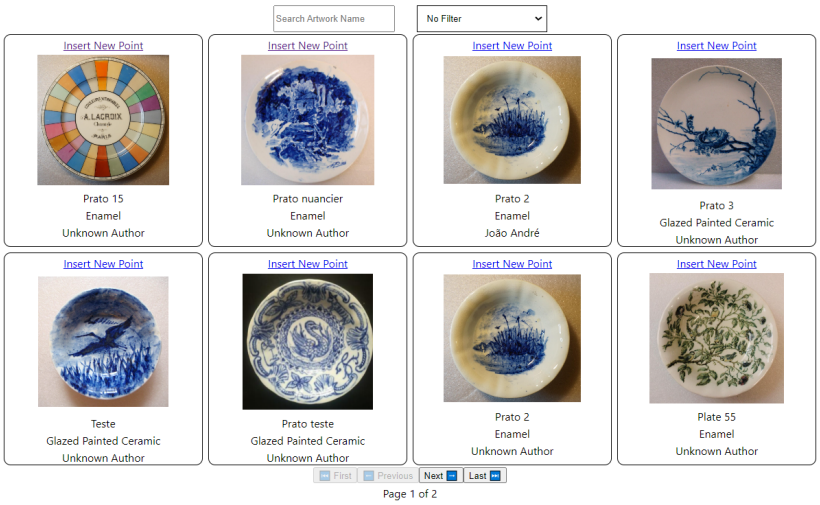


Figure 5.13: Artwork Gallery.

Figure 5.13 displays an image from the first page of the gallery, showcasing 8 artworks, arranged in rows of 4. In case the search results are extensive, users can navigate through pages using the options provided at the bottom of the current page. To be able to use pages (pagination[15]), a pagination class, which can be seen in Figure 5.14a, was designed and developed based on the react-paginate[16], but with a simpler interface and methods. In Figure 5.14b, it is possible to observe how the pagination class is applied in the code. The "activePage" variable initially starts with a value of 1 and is updated in the pagination class through the setActivePage function, which is a React hook[17]. The variable "rowsPerPage" is set with a hard-coded value of 8, indicating a total of 8 pictures per page. The "count" variable represents the length of the array generated by the "filterRows" function explained before (Figure 5.11). Lastly, the "totalPages" variable is derived from the

[15] https://www.techtarget.com/whatis/definition/pagination
[16] https://www.npmjs.com/package/react-paginate
[17] https://legacy.reactjs.org/docs/hooks-intro.html

formula Math.ceil[18](count / rowsPerPage), which calculates the smallest integer number resulting from the division.

```
export const Pagination = ({ activePage, count, rowsPerPage, totalPages, setActivePage }:any) => {

    return (
        <>
            <div className="pagination">
                <button disabled={activePage === 1} onClick={() => setActivePage(1)}>
                    First
                </button>
                <button disabled={activePage === 1} onClick={() => setActivePage(activePage - 1)}>
                    Previous
                </button>
                <button disabled={activePage === totalPages} onClick={() => setActivePage(activePage + 1)}>
                    Next
                </button>
                <button disabled={activePage === totalPages} onClick={() => setActivePage(totalPages)}>
                    Last
                </button>
            </div>
            <p>
                Page {activePage} of {totalPages}
            </p>
        </>
    )
}
```

(a) Pagination class.

```
<Pagination
    activePage={activePage}
    count={count}
    rowsPerPage={rowsPerPage}
    totalPages={totalPages}
    setActivePage={setActivePage}
/>
```

(b) Pagination class use.

Figure 5.14: Pagination class and its use.

Another significant feature is the ability to list all the points within an artwork, filtered by their name layer. In Figure 5.15, we can observe the name layer filter "XRF" (X-ray fluorescence spectrometry) in use, displaying the points associated with that specific name layer. On the left side of the page, you can observe an image of an artifact (ceramic plate) with three markers (blue dots), where each marker corresponds to one of the listed points.

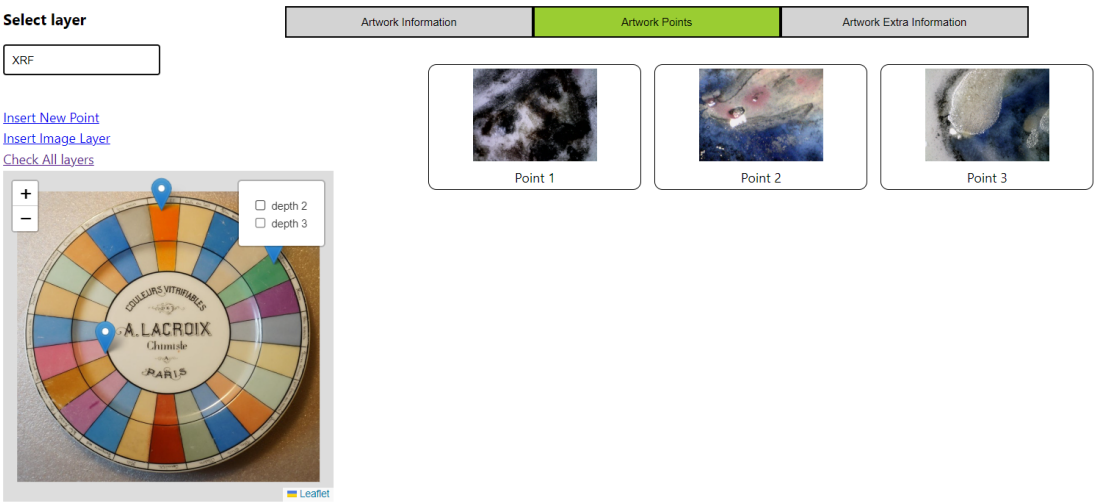


Figure 5.15: Artwork points page.

In Figure 5.16, we can find the code for incorporating Leaflet into the project. A "MapContainer" is created, with the noteworthy detail that the coordinate reference system[19] (CRS) is set to CRS.Simple, indicating a square grid. Within the map container, the ImageOverlay (background) can be easily modified, along with its bounds, which

[18] https://developer.mozilla.org/en-US/docs/Web/JavaScript/Reference/Global_Objects/Math/ceil

[19] https://leafletjs.com/examples/crs-simple/crs-simple.html

correspond to the width and height values saved earlier when uploading pictures to the system. Additionally, there are two functions: "AddLayers" (illustrated in Figure 5.17a), which inserts all the markers for the selected layer, and "AddLayers" (shown in Figure 5.17b), which adds the available image layers for the currently selected artwork.

```
return (
    <MapContainer ref={map} center={center} zoom={setZoom()} minZoom={-5} dragging={false} doubleClickZoom={false}
                  scrollWheelZoom={false} crs={CRS.Simple}>
        <ImageOverlay
            url={props.img}
            bounds={bounds}
        />
        {AddLayers()}
        {AddMarkers()}
    </MapContainer>
);
```

Figure 5.16: Leaflet usage to represent points.

```
function AddMarkers() {
    return (
        <>{props.markers.map((item: any) => (
            <Marker key={item.id} position={xy(item.positionX, item.positionY)} icon={icon} eventHandlers={{
                popupclose: (e) => {
                    // @ts-ignore
                    map.current.setView(center, setZoom());
                }
            }}>
                <Popup>
                    {"name: " + item.name}
                </Popup>
            </Marker>
        ))}</>
    )
}
```

(a) AddMarkers function.

```
function AddLayers() {
    if (layers.length > 0)
        return (
            <><LayersControl position="topright">
                {layers.map((item: any) => (
                    <LayersControl.Overlay key={item["id"]} name={"depth " + item["depth"]} >
                        <ImageOverlay key={item["id"]}
                            url={'' + item["image"]}
                            bounds={bounds}
                        />
                    </LayersControl.Overlay>
                ))}
            </LayersControl>
            </>
        )
}
```

(b) AddLayers function.

Figure 5.17: Leaflet additional functions.

On this page, users also have the option to add new points to the system. If a point within an image is selected, the user is redirected to the corresponding point page, where these point features are explained in more detail in Section 5.3.1.2. Additionally, users can insert image layers and access all the image layers associated with the current artwork. Image layers are images captured from the same perspective and point of view as the artwork image, as shown in Figure 5.18a. However, they have different spectrum lights and opacity levels applied to create new images visually, as demonstrated in Figure 5.18b. Figure 5.18 provides a visual comparison between these two types of artwork images.

After understanding the concept of image layers, it's essential to grasp why and how they are used within the system. Figure 5.19 illustrates how image layers can be added to an existing artwork. Similar to the artwork insertion process, users must upload an image and complete the mandatory fields to activate the button, making it ready for use. If a user wishes to review, edit, or remove any of the added image layers, they will be redirected to a page containing those options, as shown in Figure 5.20.

Extra Information and PDF Files

(a) No lights applied.

(b) Different lights applied.

Figure 5.18: Differences from an original artwork image and a modified one.

Figure 5.19: Insert Image Layers.

Figure 5.20: List of Image Layers.

In addition to the standard information associated with each artwork, users can efficiently add new pieces of information related to a specific artwork using the "Artwork Extra Information" page. Users have two different options, as shown in Figure 5.21. They can either directly add important PDF files, which can later be downloaded and reviewed by researchers or the general public, or they can add links and scattered pieces of information within a table. The latter option allows users to group this information together, simplifying the researcher's task of searching for relevant details.

Figure 5.21: Extra Information and PDF Files.

5.3.1.2 Relevant Artwork Locations (Points)

After analysing all the available features in the artwork area, it is important to also review the features related to points. Points are enlarged photos of specific portions of the artwork, designed to aid researchers in studying each part of the artwork individually. Often, these points are extracted to facilitate the study of their mineral composition and to examine the distinctions between various points being analysed within the artwork. As previously shown in the Artworks Section (Section 5.3.1.1), a feature for inserting corresponding textual data and image data for points was created and further developed, enhancing the system's capabilities. Users can press the "Insert New Point" button either in the artwork gallery (Figure 5.13) or on the artwork point page (Figure 5.15), located just above the artwork picture.

In Figure 5.22, the insert enlarged point page is displayed, allowing users to add information associated with a point. The process begins by the user choosing the point location (by clicking on the artwork figure) within the artwork image. Next, the user must upload the image file of the enlarged picture and fill in the mandatory fields with the corresponding data. Once all data processes are correctly completed and the required information is provided, the button becomes active, allowing the user to save the point data and associate it with the artwork.

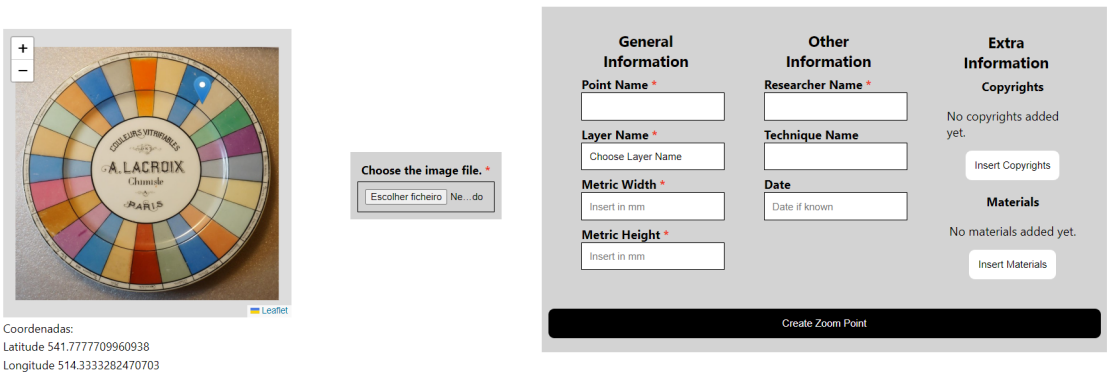


Figure 5.22: Insert enlarged point page.

Leaflet is part of the process of recording the point location within the image (after

the user clicks on it), and the coordinates are presented below the leaflet grid area. Another "MapContainer" is depicted in Figure 5.23, which also includes the ImageOverlay (for altering the background picture) and a marker whose position is managed by the "SavePosition" function. When the user clicks on the image, that function is invoked, and the click event records both the longitude and latitude, as shown in Figure 5.24. These recorded values will subsequently be transmitted as part of the point information, enabling their display on the artwork points page later.

```
<div className={"Teste"}>
    <main>
        <section>
            <MapContainer ref={map} center={center} zoom={y>1700?-3:y>900?-2:-1} minZoom={-5} maxZoom={0}
                          dragging={false} doubleClickZoom={false} scrollWheelZoom={false} crs={CRS.Simple}>
                <ImageOverlay
                    url={props.img}
                    bounds={bounds}
                />
                {position.latitude !== 0 ? (
                    <Marker
                        position={[position.latitude, position.longitude]}
                        interactive={false}
                        icon={icon}
                    />
                ) : null}
                <SavePosition handlePos={handlePos}/>
            </MapContainer>
            <div className={"Coordenadas"}>
                <>Coordenadas: <p/>
                    Latitude {position.latitude} <p/>
                    Longitude {position.longitude}
                </>
            </div>
        </section>
    </main>
</div>
```

Figure 5.23: Leaflet class code to insert points.

```
function SavePosition({handlePos}){

    useMapEvents( handlers: {
        click(event : LeafletMouseEvent ) {
            const { lat, lng } = event.latlng;
            handlePos(lat, lng);
        },
    });
    return (
        <div/>
    );
}
```

Figure 5.24: Function SavePosition from Leaflet.

As previously shown in the Artwork Page for points (Figure 5.15), if there are any enlarged points in the selected layer, they will be presented there. If the user selects one of the points, they will be redirected to the point page containing all its information. This page is depicted in Figure 5.25, and here, users can also edit any point data or even delete the point from the system.

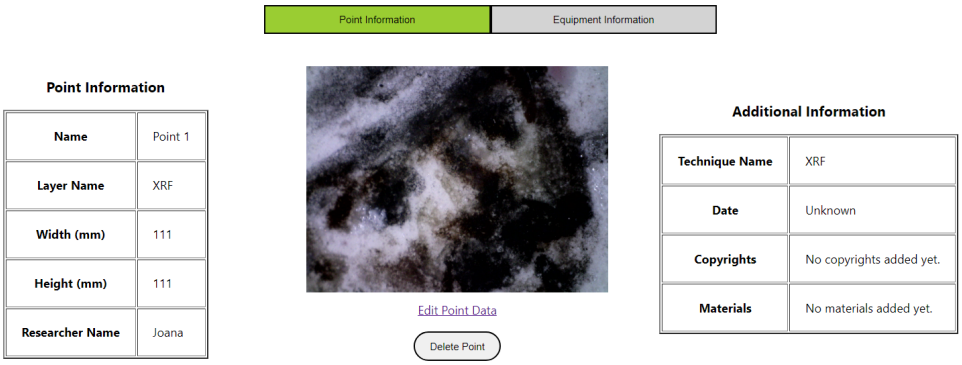


Figure 5.25: Informational page for points.

Equipment

Similar to artworks, equipment can also have additional information and PDF files assigned to them. One example are camera lenses, as illustrated in Figure 5.26. On this page, the equipment name, characteristics, and licenses (if any) are displayed, along with two buttons that allow users to edit or remove the equipment, whether they are researchers or administrators.

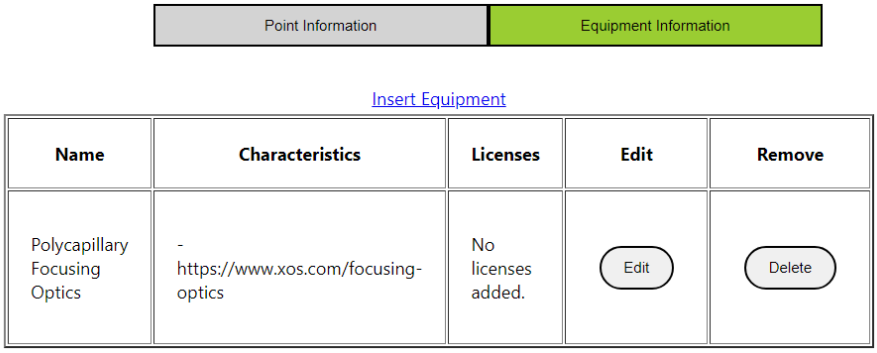


Figure 5.26: Equipment page for points.

Special Enlarged Points

The concept of points has been previously introduced and explained. Now, a new type of point called "special points" is being introduced. Special points are enlarged points with the capability to contain other points within them. Unlike regular points, which are associated with an artwork, these special points act as artworks themselves to other points. They are exclusively available in specific layers, added by an administrator, for this purpose. The introduction of special points aims to enhance the presentation of specific information in these layers. They not only accommodate enlarged pictures (regular points) but also facilitate the inclusion of graphs, charts, or other essential information.

In Figure 5.27, the selected layer is named "SEM" (Scanning Electron Microscope), one of the layers that contains special points. Unlike other layers, as shown in Figure 5.15, this layer offers additional options within the points box area. Users can either add a new special point by clicking "Insert New Point" and will be redirected to the point insertion page (Figure 5.22), or they can select "See Points" to access a page where they can view all the added points for the selected special point. This extra options are made possible by the code snippet presented in Figure 5.28. On this page (Figure 5.29), users can also click on a point's picture to be redirected to an informational point page, as demonstrated earlier in Figure 5.25.

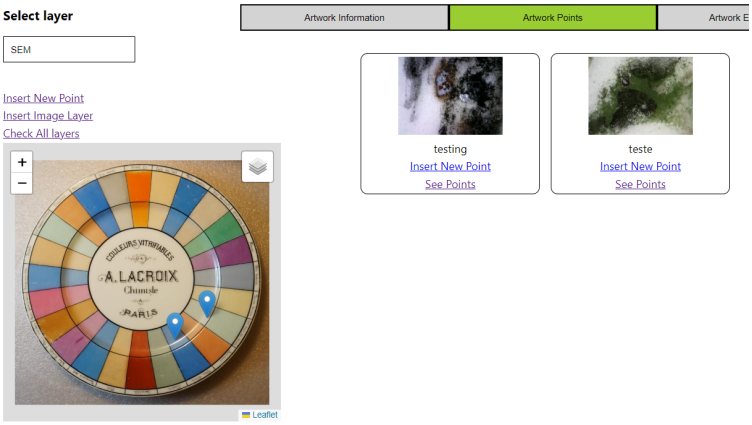


Figure 5.27: A layer that accepts special points is selected.

```
function printInformation(item:any){
    if(filter.multiplePoints){
        if(roleLogged === RESEARCHER || roleLogged === ADMIN){
            return <><p>
                <Link to={"/insert_point/" + item.id} state={{
                    img: '' + item.image,
                    artId: null,
                    x: item.pixelWidth,
                    y: item.pixelHeight,
                    pointId: item.id
                }}>Insert New Point</Link>
            </p><p><Link to={"/point/" + item.id}>See Points</Link></p></>
        }else {
            return <p><Link to={"/point/" + item.id}>See Points</Link></p>
        }
    }
    return <></>
}
```

Figure 5.28: Special points extra features.

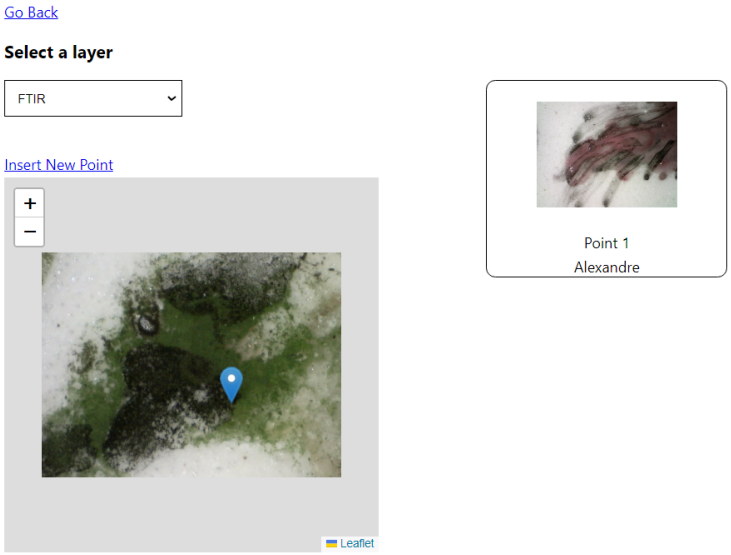


Figure 5.29: Special points page.

5.3.2 Back Office Operations

In this section the back office operations are listed and explained why they are needed in the system, but also why they must stay hidden from regular users. These functionalities help the administrators to have more control of the whole system by using these tools and making adjustments.

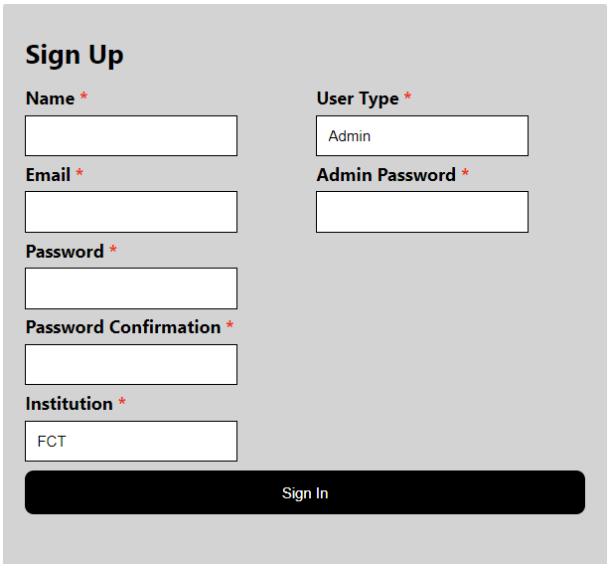
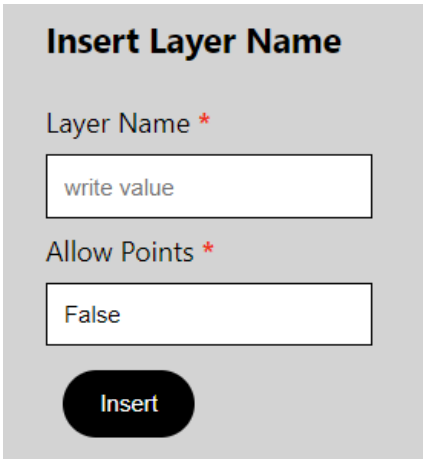


Figure 5.30: Back Office Sign Up.

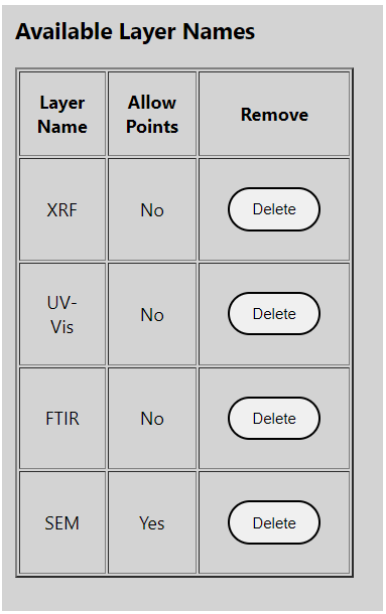
The first operation is a sign-up page, as shown in Figure 5.30, but it is not a regular sign-up accessible to everyone. Here, individuals enrolling in the system can choose from all the available roles (student, researcher or administrator). The higher the chosen role, the more features and functionalities the person has access to. To complete the sign-up successfully, individuals must input the corresponding password value for their

selected role in the form. This approach can help save time and resources for system administrators, as they only need to share the corresponding password value for the role during the sign-up process.

The second page is related to which spectroscopy analysis (layer) the artwork belongs to. An administrator can insert new layers into the system with their respective names and if points present in that layer can be associated to other points (this layer contains special points, Section 5.3.1.2). Figure 5.31a provides visual context of the layer insertion operation to the system. On the same page, there is a listing of all available layers, along with the option to remove a layer from the system, as shown in Figure 5.31b. Deletion is only possible if there are no artworks associated to that respective layer.



(a) Layer Name Insertion.



(b) List of Available Layer Names.

Figure 5.31: Back Office Layer Names.

The next functionality ensures that system administrators can change a user role without help from the IT department. The administrator just has to insert the email of the user which role is to be changed and the new role for that user. If the new role is not a regular one (student), the administrator also has to insert a code to be able to complete the operation. To avoid system malfunctions, an administrator cannot lower the role of a fellow administrator. The operation explained is displayed in Figure 5.32.

The last back-office operation is one of the most important ones in the system, since allows the administrators to manage the system secrets (codes). These codes are a must in the system because if someone unauthorised tries to exploit the system, it would be almost impossible to discover these codes values. The secrets ensure that only authorised personnel (people who got to know the secrets values from an administrator) are able to use the back office and also other important functionalities of the system. Such operations

are the ones listed above and also all the delete operations (to remove artworks, points, etc... from the system). The secrets page can be seen in Figure 5.33.

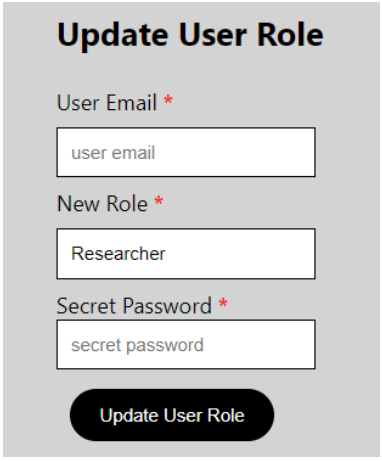


Figure 5.32: Back Office Update Another Person Role.

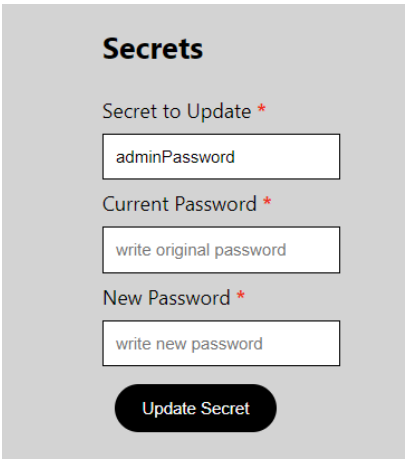


Figure 5.33: Back Office Secrets.

6

Evaluation and Results

This chapter serves as an introduction to the evaluation and validation of the proposed solution. It begins by outlining the informal evaluation moments (Section 6.1) and how they contributed to more effective testing of the application during its development. Subsequently, in Section 6.2, it encompasses the final prototype evaluation conducted by professional personnel, outlining its objectives and outcomes. Finally, the chapter includes a discussion of the results obtained from all evaluations, with a particular focus on the last one.

The evaluation methodology employed for the resulting system encompassed two primary avenues of analysis, informal and formal evaluation methods. The informal methods were used before the system was completely developed to guarantee that the requirements elicited earlier in Section 4.2, were being followed. Informal tests also assisted in ensuring product quality, both concerning the initially identified requirements and the modification or even addition of new functionalities (functional requirements) to the system. Two informal evaluation instances were conducted, and these will be addressed in section 6.1.

The second evaluation method, formal tests and evaluation phases are crucial in any project for their key role in assuring quality and adherence to established standards. These assessments act as important checkpoints, helping to spot and address potential issues and deviations from project goals, and help prevent costly mistakes. They also provide stakeholders with objective insights, facilitating informed decision-making. Ultimately, integrating formal testing and evaluation phases significantly contributes to a project's success, building confidence in its results and enhancing overall effectiveness. A explanation of what was accomplished during this evaluation period can be found in section 6.2.

6.1 Informal Evaluations

There were two important distinct informal evaluation moments throughout the work. The first one was mentioned in Section 4.3, which was the last meeting for mockup analysis

and testing with the main project stakeholders. The stakeholders are member of the VICARTE research unit from NOVA university. The primary objectives of the mockup and its evaluation were to determine whether the available features were sufficient or necessary for the system. The evaluation mockup also contributed to the enhancement of the design and system usability, even though these aspects were not the primary focus at this point.

Because it was an online paper mockup with limited potential interactions between pages, there was no requirement to develop a task analysis for stakeholder guidance. Consequently, the stakeholder could freely explore the mockup and assess whether any crucial features were lacking in the system. Most mockup features were retained in the system. However, a page containing all the authors of artworks was removed, as its inclusion would have significantly increased the workload and development time. This decision was made because it was not a system requirement. As previously mentioned, besides the removals, most of the current back-office operations were also added after the mockup testing. Additionally, it significantly contributed to adapting certain pages, not only in terms of design but also in how the information should be displayed. This was done to ensure that future users would have an improved work experience when using the developed system. The primary design alteration enables users to simultaneously view multiple points within a layer, eliminating the need to search through the image for different points, thereby saving precious users' time.

The second informal pivotal evaluation moment occurred when every feature had already been developed, with only some minor details remaining to complete the intended application. These missing details included the need for some pages to undergo design improvements or adjustments to the existing design, as well as the incomplete development of certain administrator back-office operations, which were not essential to the system's smooth operation. As in the previously mentioned evaluation moment, there was no script or task analysis to follow; the stakeholder was free to test any aspect of the system, except for the back-office operations that were incomplete. From these tests, it became evident that one feature was not yet performing to its fullest required potential and some pages needed a design upgrade, not only to be more visual appealing but also to help solve some usability problems. Some of the pages during this evaluation are present in the annex page I.

As detailed in Section 5.3.1.2 in the Special Points paragraph, there was still a requirement to incorporate more information into specific layers. Therefore, the concept of "special points" and how they would be integrated and function within the current system design were possible because of this particular evaluation moment. It also became evident that artwork-related pages had design and usability concerns for every type of user in the system. This made data insertion more challenging than it should be, and the presentation of informational data was not in a very logical order. These matters were later addressed and modified to create the current artwork pages, as shown in Section 5.3.1.1. The modifications that were implemented were forward-thinking and prepared

the artwork page for facilitated scalability in future work. In addition to recognising the need for design upgrades and the introduction of a completely new feature (special points), there was also a requirement for additional administrators' back-office operations. Some of these newly suggested operations were straightforward yet highly useful for managing the system. These new operations included 'insert layer name' and 'update user role,' as shown in the back-office operations section in Section 5.3.2.

6.2 Formal Evaluation

In this section, the formal evaluation and validation tests are described. This evaluation occurred after all the design and feature updates resulting from the previous informal evaluation had been implemented.

All (five) participants in this evaluation were either members of or affiliated with VICARTE, and they all had university-level education, with the lowest level being a master's degree. Another detail about the users is that they were all female, with their ages closely clustered, except for one participant who was slightly older. This could have biased the formal evaluation results.

6.2.1 Tasks

Before commencing the tasks, users were required to carefully read the instructions, the tasks themselves, and important observations to keep in mind while performing the tasks. Two separate task analysis were created because combining them would have been too demanding for the testers. This approach ensured that users had adequate time to rest between tasks. The first task mostly studies artwork, points and equipment features, while the second task intensively focus special points features. The usability test guide and respective Google Form are presented in Annex II.

To avoid redundancy, the following are explanations for the first five tasks common to both task analyses.

Task 1 – Login

Since the test mainly centres on privileged user operations, the first task is to log in to the system with an authorised user account to ensure that incorrect privileged account usage would not be a factor and influence the results and its corresponding evaluation. This task is quite straightforward, so no problems appeared during its execution.

Task 2 – Insert an artwork

In this task, users are tasked with inserting a new artwork into the system. The process involves entering the artwork insertion page, which is located in the navigation bar. On this page, users must provide mandatory textual information and upload a picture of the

artwork. Users have the flexibility to complete the data insertion in the order that best suits them.

This task is designed to assess the users' ability to successfully insert an artwork on the artwork insertion page. The effectiveness of the page design and how the textual artwork information is retrieved are key aspects being evaluated. Additionally, it's important to note that the completion of this task is crucial, as it serves as a prerequisite for other tasks in the system.

Task 3 – Search in the artwork gallery

In the third task the user undertakes a search for the artwork introduced in Task 2 within the confines of the art gallery. Initially, the user is required to navigate to the art gallery page, which can also be accessed via the navigation bar. Subsequently, the user is tasked with the specific objective of locating a particular artwork in the gallery. The user has the option to either perform a comprehensive search of all available artworks and all its pages or employ the search and filter features for a more expedited retrieval. After finding the artwork the user has to access its informational page.

This task serves the purpose of assessing user responses when they are tasked with the retrieval of artwork. This functionality is relevant, particularly in scenarios where there is a substantial volume of artworks, numbering potentially in the hundreds or thousands, making it impractical to manually search through each page until the desired artwork is located.

Task 4 – Insert an image layer

After opening the artwork page in the last task, the user now needs to access the Artwork Points page and find out how to insert a new image layer in the system. After finding the clickable link, the user is redirected to the image layer insertion page. Here, like in the artwork insertion, the user has to provide mandatory textual information and the picture to be added.

This task aims to determine whether, after a user accesses the homepage of an artwork, it is clear how to proceed to the next step (transitioning to the points page) and being redirected to the image layer insertion page. On the insertion page, we intend to assess both design improvements and the overall user-friendliness of its usage.

Task 5 – Change the artwork image background

In this task, after successfully insert the new image layer, the user is already in the page where he has to perform the image background change.

This task aims to assess whether the user can understand how to change the background image from the original artwork photograph to the newly added image. This allows us to measure the ease or difficulty users experience in completing the task.

6.2.1.1 Task Analysis One

The first set of tasks covers all the key features related to artwork and equipment, while also addressing certain aspects of points.

Task 6 – Insert a PDF file

In task 6, the user is required to navigate to the 'Artwork Extra Information' page, from where they can be redirected to the PDF file insertion page. On the insertion page, users simply need to input the information and save it within the system.

This task serves as a test of the design of the artwork pages, as well as an assessment of the intuitiveness of the PDF file insertion page for users.

Task 7 – Search for a PDF file in the artwork

In this task, after successfully inserting the PDF file, the user needs to understand how to return to the previous page. Upon returning, the user must locate the added PDF file within the PDF files list.

This task evaluates the user's ability to navigate the artwork pages smoothly and locate the specific file they are searching for. It complements the previous design tests conducted on the artwork pages.

Task 8 – Insert a point

In task 8, the user is required to navigate to the 'Artwork Points' page and understand how to be redirected to the point insertion page. Alternatively, the user can also go to the gallery, locate their artwork, and be redirected to the insertion page from there. On the insertion page, the user must complete all mandatory information to execute the action.

This task serves as a continued evaluation of the design of the artwork pages and their intuitiveness for users. Additionally, it assesses the user's capability to successfully add a point on the point insertion page, with a focus on evaluating the effectiveness of the page design and the retrieval of both the point's location and textual information.

Task 9 – Open point information page

After successfully inserting the point in the previous task, the user must now navigate to the "Artwork Points" page, if they are not already there, and search for the corresponding layer, which is associated with the point. Once the user finds the inserted point, they must open the information page for that point.

This task represents the final evaluation of the artwork pages' design. It extends the assessment to include testing the layer search feature within the "Artwork Points" page and aims to appraise how intuitively users understand how to access the point page information.

Task 10 – Insert an equipment

In this task, the user is required to navigate to the "Equipment Information" page and discover how to be redirected to the equipment insertion page. On the insertion page, the user must complete all mandatory information to successfully complete the task.

This task evaluates whether users can effortlessly navigate the Point pages and locate the button for redirection to the equipment insertion page. Furthermore, it assesses the user's ability to effectively add equipment to the system, with a specific focus on evaluating the page design and the retrieval of equipment information.

Task 11 – Edit the equipment information

In task 11, the user is already on the page where they can locate the redirect button. The user's objective is to search for the equipment and press the button to begin editing its information. Upon redirection, the user can modify the information as desired. After the edition is complete the user has to save the information.

This task aims to assess whether the user can easily locate the button to be redirected to the equipment edit page. It also serves as a test to evaluate the intuitiveness of the edit page and the user's ability to make changes to the equipment information with ease.

Task 12 – See the edit results

In this task, there is no need for navigation assessment, as the user is already on the page containing the table of data they want to review and compare after completing the editing operation. The user simply needs to search the equipment table, locate the row corresponding to their equipment, and confirm the changes.

This task is not only essential for testing the equipment editing feature but also serves as a way to educate users that their equipment edits may lead to updates in the equipment table.

Task 13 – Remove equipment from the system

In task 13, much like tasks 11 and 12, the user is already situated on the page where they have to find the method to delete the specified equipment from the system. After identifying the equipment in the table, the user must press the delete button to trigger the appearance of the delete confirmation window. Within this confirmation window, the user must enter a code to initiate the removal of data from the system.

This task is designed to assess whether the user can easily locate the delete button and successfully remove the equipment's data entry from the system. It also serves as a test to evaluate the intuitiveness of the delete confirmation window and the user's capability to complete the deletion process with ease.

6.2.1.2 Task Analysis Two

The second set of tasks comprehensively addresses all the essential features related to points and includes specific operations related to special points.

Task 6 – Insert a special point

In this task, similar to Task 8 in the first set of tasks, the user has to navigate to the "Artwork Points" page and understand how to access the point insertion page. Alternatively, the user can choose to navigate to the gallery, locate their artwork, and access the insertion page from there. On the insertion page, the user is required to complete all mandatory information to execute the action. In this specific case, the user must select one of the layers that contain special points during the point insertion process.

This task represents a continued evaluation of the design of the artwork pages and their intuitiveness for users. Furthermore, it assesses the user's ability to successfully add a special point to the system, with a particular focus on evaluating the effectiveness of distinguishing between the insertion of a regular point and a special point.

Task 7 – Search for the special point inserted before

After successfully inserting the special point in the previous task, the user must navigate to the "Artwork Points" page, unless already there, and locate the corresponding layer associated with the special point. Once the user finds the inserted special point, the task is considered complete.

This task serves as another evaluation of the artwork pages' design and expands the assessment to include more testing of the layer search feature, within the "Artwork Points" page.

Task 8 – Insert a point in the special point

The preceding task has set the stage for the current task, making it easier for the user as they are already in a position to press the button to insert a point associated with the special point created earlier (task 6). Similar to task 6, the user needs to upload a picture, specify the point's location, and provide textual information, but this time, there are no prerequisites for selecting a specific type of layer.

This task continues the evaluation of the design of the artwork pages and their user-friendliness. Furthermore, it holds significance as the point added in this task will serve as the central focus in the subsequent tasks. This task is important for users to understand that like in artworks, they can also insert special points before entering the special point page (task 9).

Task 9 – Search for the special point and enter its page

This task closely mirrors Task 7, wherein the user is required to find the corresponding layer associated with the special point. Upon locating the inserted special point, the user must click the option to view all points contained within the special point, which will open the special point page. Once this page is accessed, the task is complete.

This task provides another opportunity to evaluate the design of the artwork pages and the layer search feature. It also aims to assess whether users can easily access the page that displays all points for a specific special point.

Task 10 – Search and open the page for the point added in task 8

Similar to the previous task, the user, now on the special points page, needs to use the search layer feature to locate the specific point in question. After finding the point, the user must click on it to access its information page.

This task marks the first evaluation of the special points page and its design, including the use of the layer search feature, which mirrors the one used in the artwork page. Additionally, it aids in determining if users can open regular point page information.

Task 11 – Edit the point information

In task 11, the user is already on the page where they can locate the button to redirect to the edit point page. The user's objective is to press the button to begin editing the point information. Upon redirection, the user can modify the information as desired. After the edition is complete the user has to save the information.

This task aims to assess whether the user can easily locate the button to be redirected to the point edit page. It also serves as a test to evaluate the intuitiveness of the edit page and the user's ability to make changes to the point information with ease.

Task 12 – See the edit results

In this task, there is no requirement for a navigation assessment since the user is already on the page containing the point's data that they wish to review and compare after completing the editing operation. The user simply needs to review and confirm the changes.

This task is crucial, not only for testing the point editing feature, but also serves to evaluate the intuitiveness of the data alteration process.

Task 13 – Remove point from the system

In Task 13, much like Tasks 11 and 12, the user is already on the page where they need to find the method to delete the specified point from the system. The user must click the delete button to prompt the appearance of the delete confirmation window. Inside this confirmation window, the user must enter a code to initiate the removal of data from the system.

This task is designed to assess whether the user can readily locate the delete button and successfully remove the point' data entry from the system. Furthermore, it serves as a test to evaluate the intuitiveness of the delete confirmation window and the user's proficiency in completing the deletion process with ease.

6.2.2 Results

As previously mentioned, to validate the proposed solution, a series of user tests were conducted on the proposed prototype. These tests were elaborated in detail in Section 6.2.1 (Tasks). Subsequently, the feedback and results obtained for each task during the

evaluation process are presented. With the exception of one user who required some assistance to complete one of the tasks, all participants successfully completed the assigned tasks. As a result of these tests, each participant inserted an artwork into the system, which contained multiple zoom points ready for review and analysis.

To avoid redundancy, the following are results and evaluations for the first five tasks common to both task analyses.

Task 1 – Login

All participants successfully completed task 1. This task is undoubtedly the simplest of all, as it involves a standard login feature that users are familiar with from their daily use. Four of the participants executed the task without any issues. However, one user entered the incorrect password, and since the error message during login does not specify whether the email account exists or if the password is incorrect, the user had to make 3 or 4 attempts before successfully logging in. As can be interpolated from the graph in Figure 6.1 Overall, 20% (1 participant) considered task 1 easy to complete, while the majority, 80% (4 participants) considered it very easy to complete.

Given that only one user faced challenges during the login process, there were not many suggestions provided concerning the login feature. As previously mentioned, one recommendation was to explicitly indicate the type of error (whether it pertains to an incorrect email or password) when attempting to sign in.

Figure 6.1: Distribution of participants by level of difficulty at completing task 1.

Task 2 – Insert an artwork

All participants successfully inserted an artwork into the system in Task 2. First, users found out how to navigate to the artwork insertion page without difficulty. However, when uploading the artwork picture, some users inquired about the accepted file types, which are limited to .jpeg or .png files. Those who raised questions suggested that .tiff[1]

[1] https://www.adobe.com/creativecloud/file-types/image/raster/tiff-file.html

files might also be accepted, given that multiple files and graphs are often in that format. Other than that, there were no problems in uploading the artwork picture.

Most issues arose during the insertion of textual artwork information in task 2. Some users found it challenging to understand what information was required for certain fields. Consequently, a suggestion was made to include a small question mark icon next to each label, explicitly explaining the necessary information. Another suggestion was to modify the data insertion process. Since many artworks are only known by the year or even the century, it was proposed that users should have the option to input this information without being required to provide the day and month.

Furthermore, users mentioned that for broader usability, a feature to add new artwork types (e.g., metal, glass, etc.) to the system would be beneficial. There was also a suggestion regarding the inventory number and source fields. Some artworks may have two sources, such as a museum piece having the museum as one source and the location where the art was created as the other. Lastly, one participant mentioned that in the cases of sculptures, there should be an option to insert at least four artwork pictures, one for each side of the sculpture. In some cases, additional pictures for the bottom and top views may also be needed.

According to Figure 6.2, during the evaluation of the artwork insertion task, 20% (1 participant) found task 2 to be of medium difficulty, another 20% (1 participant) considered it easy, while the majority, 60% (3 participants), found it very easy to complete.

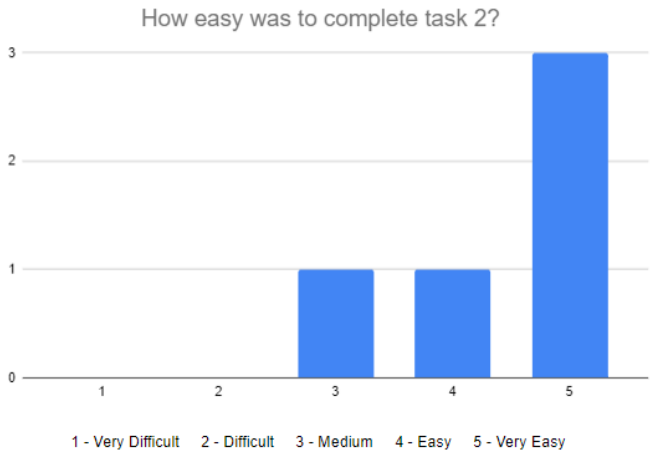


Figure 6.2: Distribution of participants by level of difficulty at completing task 2.

Task 3 – Search in the artwork gallery

All participants successfully completed task 3. Navigating to the artwork gallery page posed no issues for any of the users. Once on the page, as there were not many artwork examples available yet, most users easily located their artwork without needing to use any filtering or searching options.

This task also aimed to assess the filtering and search features, and users were asked

to attempt to find their artwork using these features. However, two users encountered difficulties in understanding how to combine both features to locate their artwork. The confusion stemmed from the assumption that when searching by name, the filtering option would be deactivated, which was not the case. Some users suggested broadening the search parameters to include the possibility of searching by artwork's source, category, and even super category.

During the evaluation of the artwork search task, 20% (1 participant) found task 3 to be of medium difficulty, another 20% (1 participant) considered it easy, while the majority, 60% (3 participants), found it very easy to complete. This information is displayed in Figure 6.3.

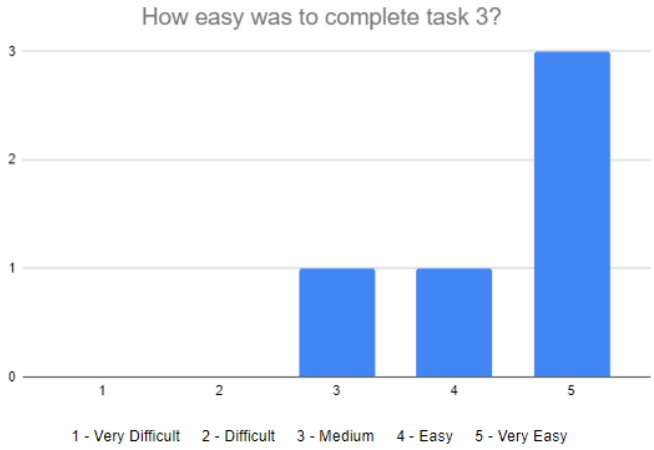


Figure 6.3: Distribution of participants by level of difficulty at completing task 3.

Task 4 – Insert an image layer

This task was where users spent the most time trying to figure out how to insert an image layer into the system. All users commented that going to the 'Artwork Points' page was not the most intuitive navigation path for the assigned task. After assisting some users in locating the appropriate page for the task, only two users immediately understood how to be redirected to the "Insert Image Layer" page by pressing the respective button. Once in the insertion process, there were no issues, as it was very similar to artwork insertion.

All users suggested changing the image layer feature to a different page or editing the page's title to make it easier to locate. Additionally, most participants indicated that the current label, "Insert Image Layer", did not adequately describe its purpose and needed to be updated to be more comprehensive.

Due to the aforementioned issues and from Figure 6.4, 20% (1 participant) found task 4 to be very difficult, another 20% (1 participant) found it difficult, and the majority, 40% (2 participants), considered it medium, while 20% (1 participant) found it easy to complete.

Task 5 – Change the artwork image background

Figure 6.4: Distribution of participants by level of difficulty at completing task 4.

This task was the second where users spent most of their time trying to figure out how to change the current artwork image background. Like in the previous task, all users commented that going to the 'Artwork Points' page was not the most intuitive navigation path for the assigned task. After assisting some users in locating the appropriate page for the task, only one user still could not understand where and how to change the artwork background image. After indicating to this participant where to look, the user was able to complete the task easily.

Similar to the previous task, most participants suggested changing the image layer feature to a different page or editing the page's title to make it easier to locate. Once on the correct page, users suggested modifying how the artwork background is changed, as some took a while to figure out that they needed to move the mouse into the artwork's top corner and assign the newly inserted artwork image.

Despite encountering some issues, users did not consider this task more difficult than Task 4. Specifically, 20% (1 participant) found task 5 to be difficult, the majority, 60% (3 participants), considered it of medium difficulty, and another 20% (1 participant) found it easy to complete. This information was retrieved from Figure 6.5.

6.2.2.1 Task Analysis One

The first 5 common tasks were already explained earlier. Now the tasks only present in task analysis one are evaluated.

Task 6 – Insert a PDF file

In this task, nearly all users successfully navigated to the intended artwork page with ease. One user took slightly more time to understand which page to navigate to ("Artwork Extra Information"). Once the participants were on the page, there were no issues in figuring out how to be redirected to the PDF file insertion page.

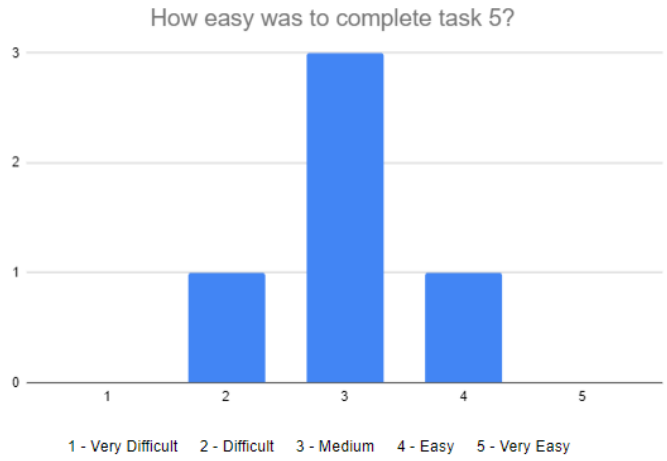


Figure 6.5: Distribution of participants by level of difficulty at completing task 5.

Since this page serves the dual purpose of inserting PDF files and other information, such as links to websites or other concepts that may not fit within the general artwork information, some users did not immediately discern which feature was being tested. Most users were expecting a button or label that would allow them to upload a PDF file for insertion into the artwork. Considering that uploading files was not an option, all users suggested adding that possibility, as most of their PDF files are stored locally on their computers and not in an online database.

During the evaluation of the PDF file insertion task, 20% (1 participant) found Task 6 to be difficult, another 20% (1 participant) considered it moderately challenging, while the majority, 40% (2 participants), found it easy to complete. Finally, 20% (1 participant) found it very easy to complete the task. This information is displayed in Figure 6.6

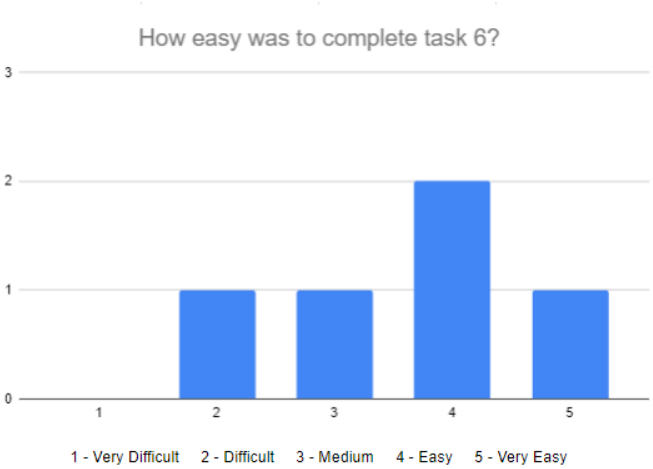


Figure 6.6: Distribution of participants by level of difficulty at completing task 6.

Task 7 – Search for a PDF file in the artwork

All participants successfully completed task 7. Since the participants were already on

the intended artwork page, there were no issues with navigation in this task. Participants only needed to search the PDF file table on their current page and locate the entry (PDF name and PDF link) they had just inserted into the system. All users were able to easily find their entry, although most of them suggested that if the pdf table had more data, there should be a search system in place, and the PDF links should be visible without the need to hover over them.

In this task, 20% (1 participant) found it moderately challenging, another 20% (1 participant) considered it easy, while the majority, 60% (3 participants), found it very easy to complete. This information is displayed in Figure 6.7.

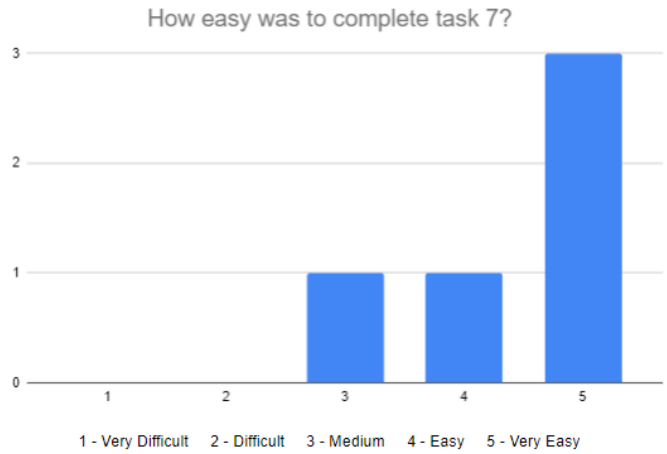


Figure 6.7: Distribution of participants by level of difficulty at completing task 7.

Task 8 – Insert a point

In this task, all participants successfully inserted a zoom point associated with their artwork. Users were required to navigate to the "Artwork Points" page, and no one encountered any issues with this step. Once on the correct page, users easily located and pressed the button to redirect them to the point insertion page.

However, in the insertion page, after uploading the point picture and filling in the textual information, some users had trouble understanding why the button was not available to be pressed for inserting the artwork. The issue was that they had not assigned the point location to the artwork. Consequently, they suggested that there should be a label or a warning to remind them to choose the point' location. Some users also recommended implementing a feature to block/unblock the ability to click on the point location to prevent unintentional mouse clicks. One participant suggested that it should be possible to insert multiple points in a row, instead of being redirected to the artwork page each time they complete the insertion. Lastly, some users expressed a desire for the option to insert the experimental parameters used in retrieving the point information.

According to the graph in Figure 6.8, 20% (1 participant) found it moderately challenging, the majority, 60% (3 participants), considered it easy, and 20% (1 participant) found it

very easy to complete.

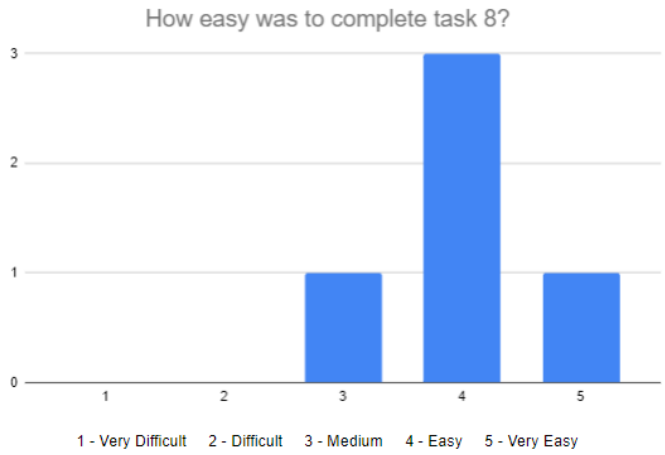


Figure 6.8: Distribution of participants by level of difficulty at completing task 8.

Task 9 – Open point information page

All participants successfully completed task 9. After the point insertion in the previous task, the participants were already on the page to complete this task. Most users had no problem figuring out how to use the layer filter option to find their inserted point. One user took more time to understand it but eventually figured it out, and there were no more issues with the filter option. After selecting the right layer, most users initially attempted to press the blue marker (dot) on the artwork picture. However, they realised that they needed to press on the point picture to be redirected to the point information page.

In this task, 20% (1 participant) found it moderately challenging, 40% (2 participants) considered it easy, and another 40% (2 participants) found it very easy to complete. This information is displayed in Figure 6.9.

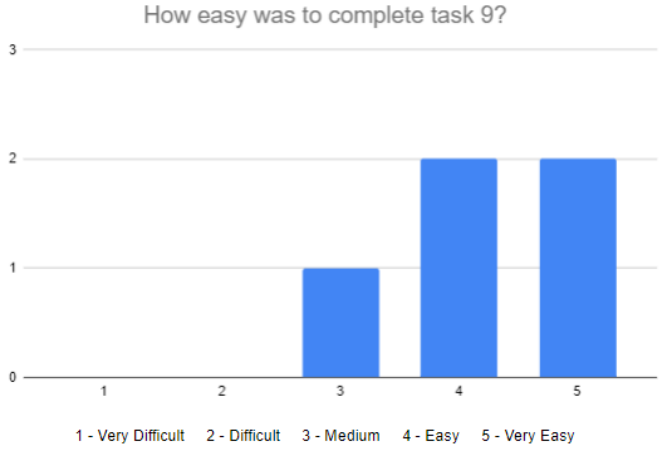


Figure 6.9: Distribution of participants by level of difficulty at completing task 9.

Task 10 – Insert an equipment

In this task, all participants successfully inserted a new piece of equipment associated with their point. All users easily navigated to the "Equipment Information" page and found the button to redirect them to the equipment insertion page. However, some users encountered issues when trying to add characteristics and licenses to their equipment due to the current design of these features. Apart from design changes, some users also suggested the addition of a button to easily exit the characteristics/licenses insertion window.

In this task, 20% (1 participant) found it moderately challenging, another 20% (1 participant) considered it easy, while the majority, 60% (3 participants), found it very easy to complete. This information is displayed in Figure 6.10.

Figure 6.10: Distribution of participants by level of difficulty at completing task 10.

Task 11 – Edit the equipment information

In this task, all participants successfully edited the new piece of equipment that was previously inserted. The users were already on the "Equipment Information" page, so there was no need to navigate to other pages. All users easily found the button to redirect them to the equipment editing page. Similarly to the insertion, some users encountered issues when trying to change their equipment' characteristics and licenses. Most users suggested, once again, revising the design of the characteristics and licenses window and adding an exit button from that window.

In parallel to the previous task, 20% (1 participant) found it moderately challenging, another 20% (1 participant) considered it easy, while the majority, 60% (3 participants), found it very easy to complete. This information is displayed in Figure 6.11.

Task 12 – See the edit results

All participants successfully completed task 12. This task required users to review the equipment information after editing it. Some users initially found the task ambiguous

Figure 6.11: Distribution of participants by level of difficulty at completing task 11.

and spent extra time trying to discern if there was more to it. The ambiguity arose from the assumption by some users that the table was ordered alphabetically when it was actually in insertion order. As a result, these users suggested changing the table' order to make equipment search easier. Additionally, most users requested a search feature for equipment names for the same reason. Lastly, some participants recommended a design improvement for the equipment table to prevent characteristics and licenses from creating excessive blank space when one of them has too much information to display.

According to the graph in Figure 6.12, 40% (2 participants) found it easy, while the majority, 60% (3 participants), considered it very easy to complete the task.

Figure 6.12: Distribution of participants by level of difficulty at completing task 12.

Task 13 – Remove equipment from the system

In this task, all participants successfully removed the piece of equipment that had undergone information editing in the previous task. The users were already on the "Equipment Information" page, so there was no need to navigate to other pages. All users

easily found the delete button to trigger the delete confirmation window. However, in the removal window, some users could not understand why, despite pressing the delete button, nothing happened. After several attempts, they realised that a code was required to successfully complete the deletion operation. Most users suggested adding an exit button in the delete confirmation window to address similar issues they encountered in previous windows, such as characteristics and licenses insertion in task 10.

This task had 20% (1 participant) who found it moderately challenging, another 20% (1 participant) who considered it easy, while the majority, 60% (3 participants), found it very easy to complete. This information is displayed in Figure 6.13.

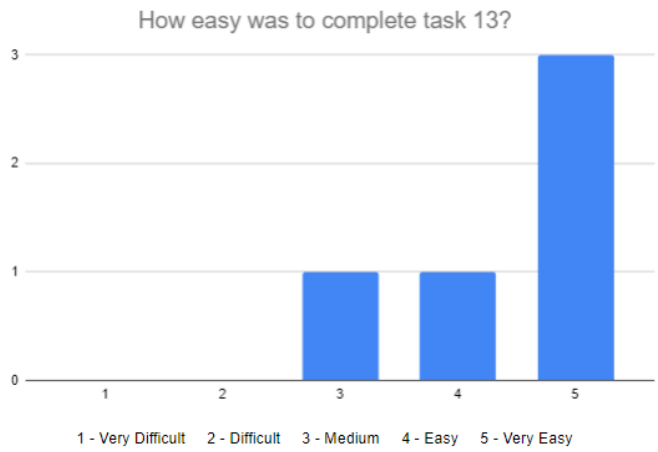


Figure 6.13: Distribution of participants by level of difficulty at completing task 13.

6.2.2.2 Task Analysis Two

The first 5 common tasks were already explained earlier. Now the tasks only present in task analysis two are evaluated. In this section, most of the task descriptions and suggestions are shorter because some tasks are similar to ones previously tested but with small yet important differences, which were necessary to be possible to complete all the tasks in this analysis.

Task 6 – Insert a special point

In this task, all participants successfully inserted a special zoom point associated with their artwork. Users were required to navigate to the "Artwork Points" page, and no one encountered any issues with this step. Once on the correct page, users easily located the button. However, before pressing it, most users mistakenly believed they needed to change the selected layer type to one that accepts points inside it (like is the case of the "SEM" layer) which is not necessary at all since the layer type selection is done in the point insertion. This task closely resembles task 8 from the first set of tasks, but in this case, users were required to insert a special point instead of a regular point, and they had to select "SEM" as the point layer for it to be considered a special point.

Since participants already knew how to insert a point from the previous task, no further suggestions were presented. However, in the insertion page, most users had issues understanding how to select the layer type required for it to be a special point. After some trial and error, all users changed the layer type to "SEM", successfully completing the task.

According to the graph in Figure 6.14, 40% (2 participants) found it moderately challenging, while the majority, 60% (3 participants), considered it easy to complete.

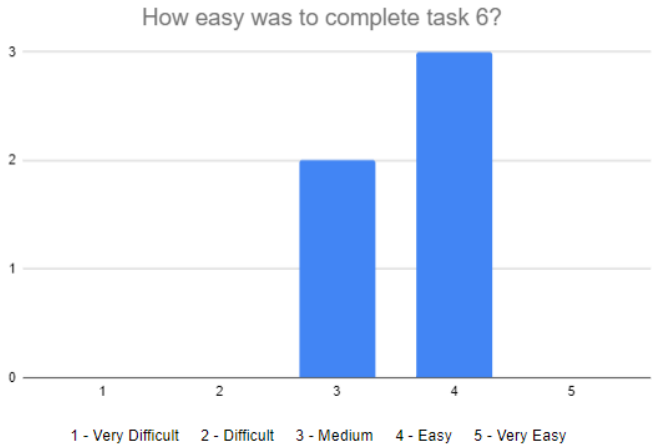


Figure 6.14: Distribution of participants by level of difficulty at completing task 6.

Task 7 – Search for the special point inserted before

All participants successfully completed task 7. After the special point insertion in the previous task, the participants were already on the page to complete this task. The users already knew how to use the layer filter option from task 9 in the first set of tasks. After selecting the right layer, users instantly found the special point they had just inserted, thus completing the given task. No suggestions or possible improvements to the layer filter options were provided.

In this task, 40% (2 participants) found it easy, and the majority, 60% (3 participants), considered it very easy to complete. This information is displayed in Figure 6.15.

Task 8 – Insert a point in the special point

In this task, all participants successfully inserted a regular zoom point associated with their special point. Users were already on the "Artwork Points" page, and this task complements the previous one, as users were already able to press the "Insert New Point" button near the special point picture when task 8 started. However, some users did not notice the button near the point picture and attempted to add a regular point in the usual way, which adds a regular or another special point to the artwork instead of linking it to the special point in question. After re-searching for the special point and realising that

Figure 6.15: Distribution of participants by level of difficulty at completing task 7.

there was a button near the picture, they had no further issues. Once redirected to the insertion page, users had no problems creating another point for the system.

Some other users also did not see the "Insert New Point" button but accidentally entered the special point page and inserted the point directly on that page. This meant that those users completed task 9 before task 8, but both approaches were equally successful.

In this task, 20% (1 participant) found it moderately challenging, 40% (2 participants) considered it easy, and another 40% (2 participants) found it very easy to complete. This information is displayed in Figure 6.16.

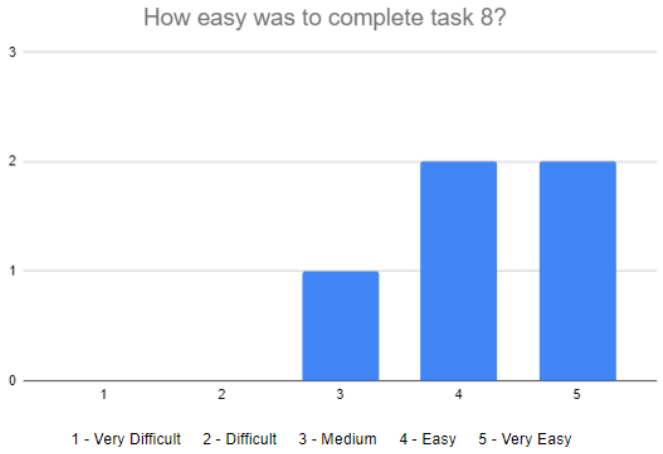


Figure 6.16: Distribution of participants by level of difficulty at completing task 8.

Task 9 – Search for the special point and enter its page

All participants successfully completed task 9. Most users were already on the "Artwork Points" page, which allowed them to complete this task efficiently. For the remaining users who hadn't completed this task yet, while doing task 8, they re-searched for the special point using the layer filter option set to "SEM." After locating the special point, some users

mistakenly thought that they should press the point picture instead of selecting the "See Points" option. Therefore, those participants suggested changing the "See Points" option to a more logical label. Some suggested alternatives included "Special Point Page" or "Points of Special Point." After accessing the special point page, users were able to complete the task.

According to the graph in Figure 6.17, 40% (2 participants) found it easy, while the majority, 60% (3 participants), considered it very easy to complete.

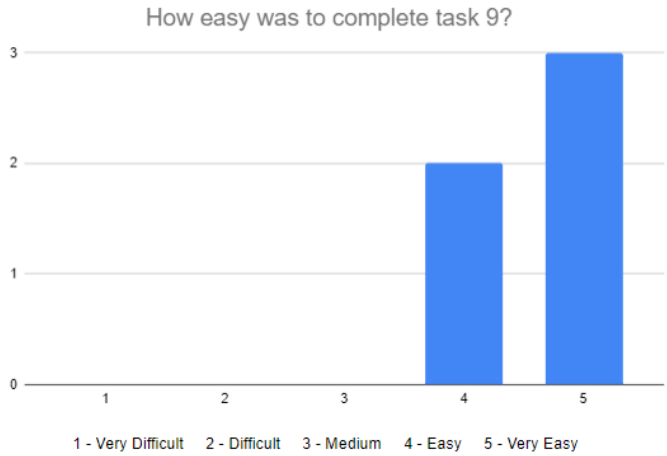


Figure 6.17: Distribution of participants by level of difficulty at completing task 9.

Task 10 – Search and open the page for the point added in task 8

All participants successfully searched for the special point and its page. Participants were already on the appropriate page to complete this task, and they had no trouble using the layer filter option to locate the inserted point. Once they found the point, users pressed on the point figure to access its page information, thus completing the given task.

Some users suggested that it might be more intuitive to allow users to open the point page by clicking on the blue marker (dot) on the artwork picture or adding a button below the point picture as alternative methods

In this task, 40% (2 participants) found it easy, while the majority, 60% (3 participants), considered it very easy to complete. This information is displayed in Figure 6.18.

Task 11 – Edit the point information

In this task, all participants successfully edited the point data or information that was previously inserted. The users were already on the "Point Information" page, so there was no need to navigate to other pages. All users easily found the button to redirect them to the point editing page. Since this page has the same design as the point insertion page and users had already inserted multiple points before, they had no difficulties completing the task.

This task had 20% (1 participant) who found it easy, while the majority, 80% (4

Figure 6.18: Distribution of participants by level of difficulty at completing task 10.

participants), found it very easy to complete. This information is displayed in Figure 6.19.

Figure 6.19: Distribution of participants by level of difficulty at completing task 11.

Task 12 – See the edit results

All participants successfully completed task 12. This task required users to review the point information after editing it. The users were already on the "Point Information" page, so there was no need for navigation to other pages. Since users had already completed task 12 in the first set of tasks, they knew that the task was simply asking them to confirm that the edits were done correctly. No suggestions were provided by the participants during the task.

According to the graph in Figure 6.20, 20% (1 participant) found it easy, while the majority, 80% (4 participants), considered it very easy to complete the task.

Task 13 – Remove point from the system

In this task, all participants successfully removed the point that had undergone editing in the previous tasks. The users were already on the "Point Information" page, so it was

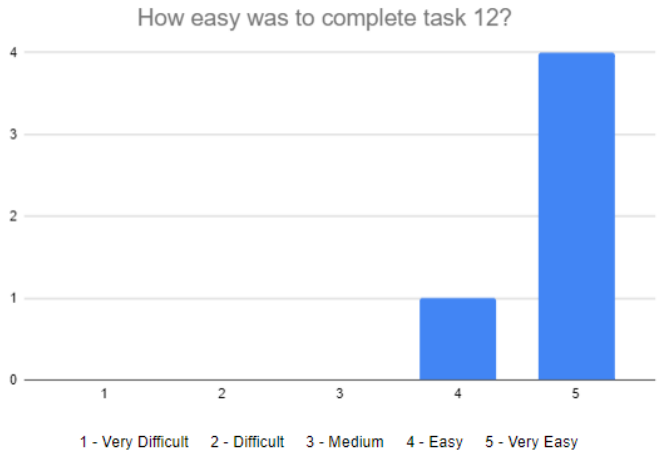


Figure 6.20: Distribution of participants by level of difficulty at completing task 12.

not required any navigation to other pages. All users easily found the delete button to trigger the delete confirmation window. Similarly to task 13 from the first set of tasks, users already knew that they had to insert a code to complete the remove process. Most users suggested, again, to add an exit button to the delete confirmation window and to make design changes on the button, so it can be more understandable when it is active or not.

This task had 20% (1 participant) who found it easy, while the majority, 80% (4 participants), found it very easy to complete. This information is displayed in Figure 6.21.

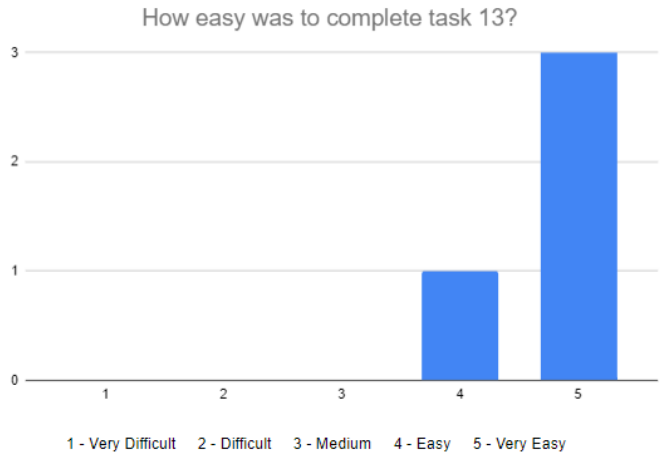


Figure 6.21: Distribution of participants by level of difficulty at completing task 13.

6.2.2.3 Results Overview

Upon completing all the tasks, the participants were provided with a questionnaire to gather feedback on the overall functionality of the application and to provide space for additional suggestions or comments regarding the tool.

As previously mentioned, all tasks were successfully completed, with only minor issues encountered during tasks 4 and 5, and one user requiring some assistance to complete task 4.

It is noteworthy that the participants had no prior experience with a similar tool for creating an artwork information repository.

Regarding the overall level of difficulty in using the tool, the results (presented in Figure 6.22) indicate that participants found the application to be of varying difficulty levels. Specifically, 20% (1 participant) considered the application to be difficult to use, 40% (2 participants) found it of medium difficulty, and the remaining 40% (2 participants) considered it easy to use.

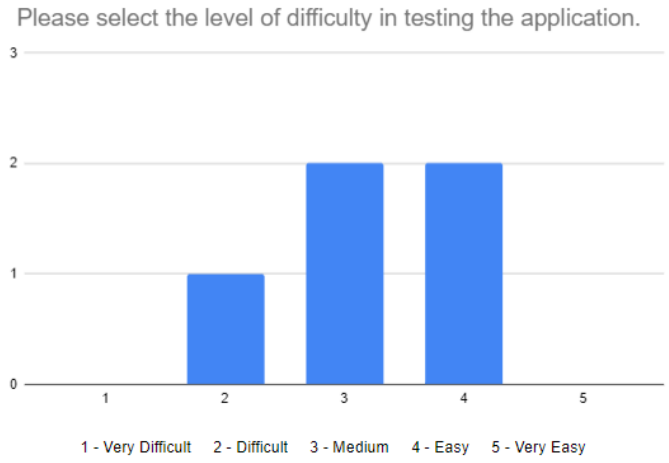


Figure 6.22: Distribution of participants by level of difficulty testing the application.

Additionally, participants were asked about their level of satisfaction with the developed tool, as shown in Figure 6.23. The results indicate that 20% (1 participant) found the application to be less than satisfactory, 40% (2 participants) considered it somewhat satisfactory, and the remaining 40% (2 participants) found it satisfactory.

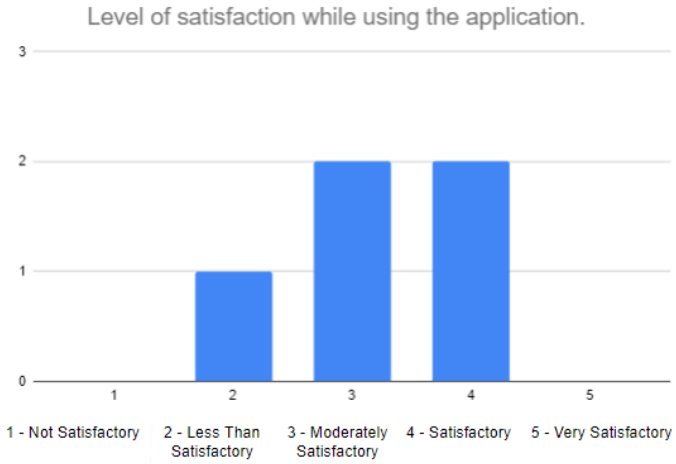


Figure 6.23: Level of user satisfaction using the application.

6.3 Summary

This chapter has presented and discussed the results and user feedback obtained during various evaluation stages.

It began by introducing the two types of evaluations used throughout the dissertation development. The first method presented was the Informal Evaluation (Section 6.1), which consisted of two distinct evaluation phases. The first involved an online mockup, which was crucial for redesigning certain pages and making changes to the system' features. The second informal evaluation took place when the prototype was nearly fully developed, but input on the system's current features and design was still sought before the final evaluation.

The final evaluation phase was the Formal Evaluation (Section 6.2), which involved a user study conducted to validate the system's functionalities, assess the quality of the artwork information generated, and determine the usability and user satisfaction when using the application. The study was conducted with a test group of 5 volunteers who completed two sets of tasks. It's worth noting that the first 5 tasks were common to both task analyses. Each set of tasks is discussed individually (Section 6.2.1), providing an explanation for the relevance of each task to the evaluation process.

The results of the user study are subsequently presented and analysed individually in Section 6.2.2. Overall, all tasks were completed successfully, with only minor issues occurring during tasks 4 and 5, where one user needed additional assistance to complete task 4. The results revealed varying levels of difficulty for each task, with tasks 4 and 5 being the most challenging. Participants provided suggestions to improve the usability of these two tasks, including complete page redesigns or relocating certain operations to other pages.

Finally, a brief Results Overview (Section 6.2.2.3) of the first formal user test is provided, along with a discussion of the process limitations encountered during the tests. The overall results indicated that users found the application moderately difficult to use. Additionally, most participants reported moderate or average satisfaction levels while using the application, although one participant rated it as less than satisfactory. This study was crucial for identifying areas of improvement in the application, with the aim of enhancing both its usability and efficiency.

7

Conclusion and Future Work

This chapter provides an overview of the work conducted throughout the dissertation, delving into the primary outcomes of the proposed solution, its strengths, and its weaknesses. Additionally it also includes Section 7.1, which offers a brief introduction to future work aimed at enhancing the current version of the developed tool.

The preservation of artworks is of paramount importance, as they encapsulate our shared human heritage and cultural diversity. These fragile treasures serve as bridges connecting disparate societies, fostering cross-cultural dialogue and mutual understanding. The loss or deterioration of artworks represents an irreplaceable loss of cultural and historical knowledge, depriving future generations of insights into our collective human story. Thus, the endeavour to safeguard and preserve artworks should remain a fundamental aspiration for humanity.

A notable example of the aforementioned need for a tool like the one developed in this dissertation can be found in the research unit VICARTE, located at the NOVA School of Science and Technology university. VICARTE's primary research objectives involve the study of glass and ceramic artworks and the preservation of cultural heritage related to these art pieces. Despite their daily involvement in the preservation and study of these artworks, they lacked a comprehensive tool to efficiently store and safeguard all the relevant information, making it instantly accessible to anyone. In the course of this dissertation, VICARTE contributed significant and valuable information on numerous artworks to be used as examples, such as enamels from the Fitzwilliam Museum and painted glazed ceramics housed at the Palácio Nacional da Ajuda. VICARTE also played a significant role in defining the requirements for the final developed application.

The research on examples of applications that implement a digital twin was crucial to reflect on the current state of the art. However, it is important to note that the majority of solutions leveraging a digital twin are primarily focused on the preservation of cultural buildings or historical sites. In contrast, this dissertation introduces a software tool tailored specifically to the preservation of cultural heritage and artworks, with a primary focus on 2D images and models of these artworks. The tool can be used by both non-professionals and the general public, with certain feature limitations for regular user accounts.

The proposed tool addresses one of the primary objectives of this dissertation, which is to create **a comprehensive data structure to organise all the information regarding the considered artefacts and their exhaustive details**. Our aim was to make the process of data insertion understandable and user-friendly for researchers in the conservation domain, as well as to ensure easy navigation for individuals with no background in conservation or engineering. The development of this solution demonstrates our capability to design and develop software that assists conservators-restorers in establishing a functional and interactive repository and website for artworks.

It is important to note that the current focus of the application primarily revolves around data insertion rather than data display. All the data within the application was collected and input by the VICARTE research team. At its current state, the application can store various information related to artworks, such as the type of artwork (e.g., enamels, glass, ceramics). It also enables users to record details about specific artwork locations (points), including the spectroscopy analysis used for that point and its precise location within the artwork. Additionally, users can input information about the equipment used for data retrieval. Furthermore, the system allows for the inclusion of supplementary information, such as links to online articles relevant to the artwork or the attachment of important PDF files associated with the artwork.

The last two proposed objectives, namely, **an outcome evaluation led by qualified personnel based on a selection of specific artifacts** and **validation of the implemented tools through user assessments**, were both achieved during the user study conducted for evaluation and validation purposes. The proposed solution underwent an evaluation through a user study, primarily focusing on assessing the tool's functionality and user acceptance. This evaluation also helped identify certain design issues.

The study revealed that the tool's level of difficulty varies and can be considered moderately challenging for inexperienced users. Users also expressed a moderate level of satisfaction with the overall features. The results indicate that there is room for ongoing improvement, including potential design updates for certain pages and revisions to the PDF file insertion methods, among other enhancements.

However, it is important to note that the evaluation process had some constraints. These limitations include the small number of participants and a lack of diversity in participant profiles, such as a narrow age range.

7.1 Future Work

While developing the system and conducting user testing sessions, participants provided valuable insights and suggestions for development and overall improvements to the application. To guide possible future work, we took into account the feedback provided by the study's participants and the notes on observed interactions to help plan the redesign of certain aspects of the tool and implement some of the given suggestions.

Considering the feedback received during the final evaluation, we have defined specific goals for what could be the next phase, which will focus on enhancing the current prototype. Some of the improvements that need to be addressed include:

- **Artwork type** – A new feature should be added, similar to the layer insertion/removal operation presented before. This feature should also only be available to system administrators to avoid potential issues with names or the insertion process itself. This new feature would help manage the available artwork types when inserting an artwork.
- **Artwork able to include multiple pictures** – For sculptures, there ought to be a provision for adding a minimum of four images depicting the sculpture' sides. Moreover, certain sculptures may require additional images for the bottom and top perspectives. This enhancement could also be beneficial for other types of artworks, where the new artwork pictures could be used for tests or other important comparisons.
- **Re-design some pages** – Several pages were identified by users as requiring design updates. The pages that received the most mentions were the window for inserting materials and additional information for artworks, as well as the characteristics and licenses sections for equipment.
- **Artwork image layer feature** – This feature proved to be the most challenging for participants when attempting to complete the assigned tasks. Several participants recommended either creating a separate section on the artwork page dedicated solely to this feature or renaming "Artwork Points" to "Artwork Points & Image Layers".
- **Improve systems' security** – The overall security for all parts of the system should be improved. The server side of the system project has spring security but it could be enhanced further and the website could also be upgraded, by setting up an SSL or TLS certificate[1] in the host server.

Other than improvements to the current system, during the development of this dissertation, another project with a similar objective was initiated. This separate project focuses exclusively on 3D models. The ultimate goal for the future is to merge both applications, creating a comprehensive data structure for both 2D and 3D objects. Once this merger is successfully completed, the final objective is to use all the gathered data to initiate the creation of a digital twin for a selected artwork.

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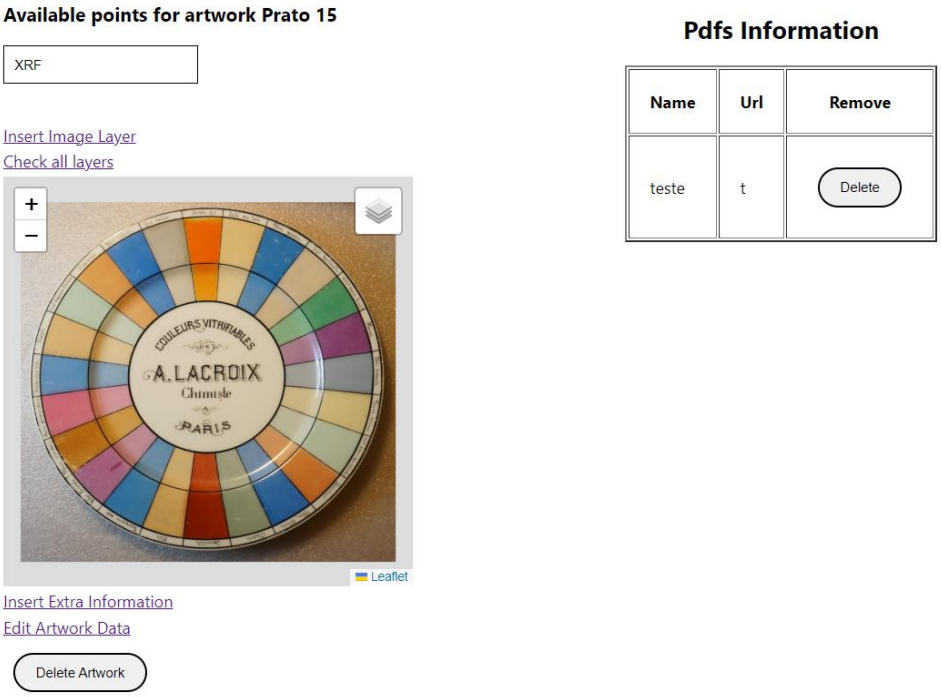
I

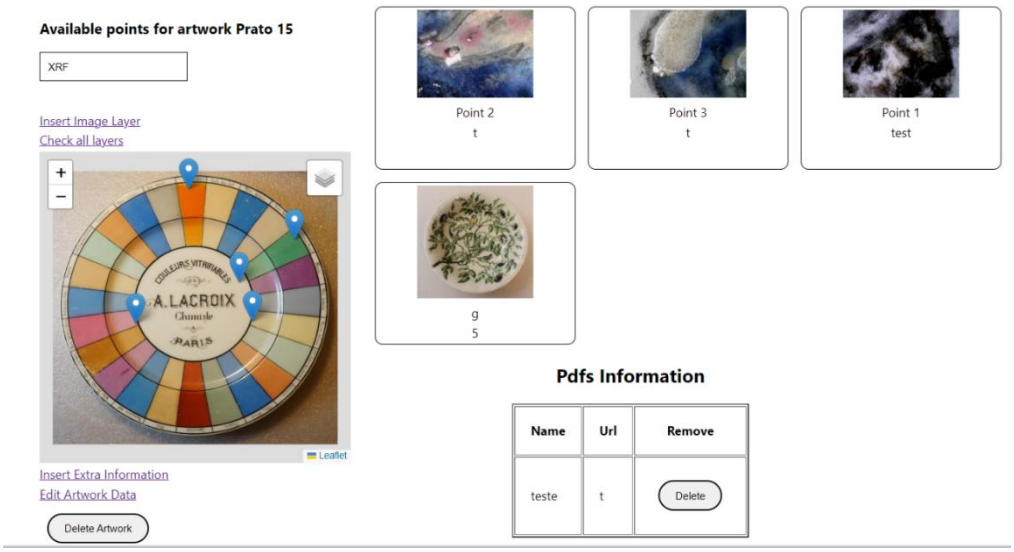
Prototype Previous Pages

During the application development, there was an informal evaluation session, in which the artwork and point pages were reviewed as shown below.

Artwork page when there are no available points to be displayed.



Artwork page when there are available points to be displayed.



Point page

Point Information

Insert Equipment

Point 1

test

Edit Point Data

Delete Point

Equipments Information

Name	Edit	Remove
camera testing example	Edit	Delete

II

Usability Test

The annex includes the necessary documentation for the usability tests. The initial document is the participant's test guide, which contains instructions for each of the tasks that participants needed to complete.

Additionally, the form that participants completed during the testing process is also provided. This form recorded the test results and gathered feedback from the participants. It is important to note that, in addition to the questions covered in this document, additional feedback was collected during the individual testing sessions.

Guião de Teste de Usabilidade

NOVA LINCS, Departamento de Informática, Faculdade de Ciências e Tecnologias, Universidade NOVA de Lisboa

Sistema para Armazenamento e Interação com Obras de Arte
Avaliação de Usabilidade

Descrição

Este documento visa guiar o participante nas tarefas que compõem a fase de teste da aplicação desenvolvida.

O trabalho tem como objetivo o desenvolvimento de uma aplicação para guardar e estruturar informações importantes sobre obras de arte, num trabalho conjunto da VICARTE e do NOVA LINCS.

No trabalho, foi desenvolvida uma aplicação web em que os utilizadores podem procurar e aceder às várias obras de arte e respetivas informações. A aplicação está desenvolvida a pensar nas funcionalidades necessárias para construir uma coleção de informação confiável sobre várias obras de arte.

Antes de iniciar a aplicação, certifique-se que está conectado com uma conta com permissões (researcher ou admin), pois será necessário introduzir novos artefactos e outras informações no sistema. Caso não tenha uma dessas contas, veja o guião de como utilizar o Website e fale com um administrador do sistema (Professora Márcia Vilarigues) caso tenha dúvidas de como obter uma.

Comece por ler atentamente as duas tarefas seguintes e os seus respetivos passos. Após ler atentamente as duas tarefas, entre no link do formulário que deve preencher calmamente para evitar erros. Pode escolher realizar apenas uma das tarefas apresentadas, ou pode fazer as duas. Existem duas opções de escolha de teste, caso queira pode escolher entre uma delas ou realizar as duas.

Comentários no fim do questionário são encorajados, pois tal ajudará o trabalho avaliativo e auxiliará a melhorar as funcionalidades e a apresentação do sistema desenvolvido.

Link de acesso ao formulário a preencher enquanto realizar as tarefas: formulário.

Tarefas

As tarefas abaixo visam verificar a facilidade e usabilidade de algumas das funcionalidades principais do sistema desenvolvido.

Observações:

As contas utilizadas para estes testes serem realizados devem ser “researcher” ou superior.

Ponto **3** – Caso não consiga encontrar a sua obra de arte adicionada na listagem, vá ao seu perfil que tem a sua lista.

Ponto **4** – Caso a obra de arte que inseriu não tenha outras imagens com diferente frequência de luz e/ou transparência, ignore este e o passo 5.

Ponto de análise – É um ponto ampliado de uma zona especifica de uma obra de arte em que os investigadores possuem informação importante para análise do mesmo.

Ponto de análise “especial” – É um ponto associado a um ponto de análise em que os investigadores possuem informação importante adicional para análise do mesmo.

Para realizar o ponto **13** é necessário os utilizadores saberem a palavra passe de confirmação de eliminação de informações do sistema.

Tarefa 1

Tarefas relativas a Obra de Arte, Ponto de Análise e Equipamento

1. Caso não esteja ligado no sistema, faça login.
2. Introduza uma obra de arte à sua escolha na aplicação e as suas respetivas características.
3. Procure na galeria pela obra de arte que introduziu e aceda à sua página geral de informações.
4. Insira imagem da obra de arte com outra frequência de luz e/ou transparência. (ver observações)
5. Caso, tenha realizado o passo 4, mude a imagem de fundo para a que adicionou no passo 4.
6. Associe um novo pdf à obra de arte.
7. Visualize a informação do pdf inserido.
8. Insira um ponto de análise na sua obra de arte, com as suas respetivas informações associadas.
9. Na obra de arte procure e selecione o ponto de análise que acabou de inserir e abra a página de informações do ponto selecionado.
10. Adicione um dos equipamentos utilizados ao ponto de análise que está a visualizar.
11. Edite a informação do equipamento adicionado.
12. Analise e visualize a informação atualizada do equipamento.
13. Elimine/remova do sistema o equipamento que acabou de adicionar.

Tarefa 2

Tarefas relativas a Obra de Arte, Ponto de Análise e Ponto de Análise Especial

1. Caso não esteja ligado no sistema, faça login.
2. Introduza uma obra de arte à sua escolha na aplicação e as suas respetivas características.
3. Procure na galeria pela obra de arte que introduziu e aceda à sua página geral de informações.
4. Insira imagem da obra de arte com outra frequência de luz e/ou transparência. (ver observações)

5. Caso, tenha realizado 4, mude a imagem de fundo para a que adicionou no passo 4.
6. Insira um ponto de análise (ponto **A**) que permita associar outros pontos a este (utilizando as camadas que aceitam pontos de análise “especiais”, por exemplo a camada “SEM”) na sua obra de arte, com as suas respetivas informações associadas.
7. Procure na listagem de pontos de análise da obra de arte e encontre o ponto adicionado anteriormente (ponto **A**) no passo 6. Não o selecione.
8. Com a listagem de pontos de análise aberta, insira um novo ponto de análise “especial” (ponto **B**) associado ao ponto de análise inserido no passo 6 (ponto **A)**.
9. Procure, outra vez, pela listagem de pontos de análise associados à obra de arte e encontre o ponto adicionado anteriormente no passo 6 (ponto **A**). Selecione ver os pontos associados a este (ponto **A**).
10. Procure e selecione o ponto de análise “especial” adicionado no passo 8 (ponto **B**).
11. Faça alguma alteração (edição) aos dados deste ponto de análise (ponto **B**).
12. Analise e visualize as informações atualizadas deste ponto de análise (ponto **B**).
13. Remova o ponto de análise (ponto **B**), cujo dados foram editados anteriormente, do sistema.

Formulário de Teste: Sistema para Armazenamento e Interação com Obras de Arte

O presente questionário corresponde a um conjunto de questões sobre 2 tarefas divididas em 12 passos cada uma, que têm como objetivo avaliar as funcionalidades da aplicação desenvolvida para gerar suporte com o repositório de dados sobre obras de arte. O protótipo da aplicação é produzido como resultado do projeto de investigação na FCT NOVA em parceria com o centro de investigação VICARTE.

Antes de começar o questionário, leia atentamente as duas tarefas apresentadas e selecione quais pretende realizar, se apenas uma das duas ou ambas. Caso não consiga realizar algum dos passos apresentados, escolha a opção "Muito Difícil" e indique que não conseguiu realizar o passo "x" no fim da respetiva secção.

Por favor, leia cada passo até ao fim antes de o iniciar e procure esclarecer quaisquer dúvidas, caso estas existam. Os passos devem ser realizados sequencialmente e após a realização de cada um, deve ser preenchido as correspondentes questões no formulário. No final da execução dos passos e tarefas, terá uma seção de questões gerais sobre a aplicação com resposta aberta dedicada a comentários.

pmfranco99@gmail.com Mudar de conta

Não partilhado

* Indica uma pergunta obrigatória

Aceito participar nos testes com base na informação que me foi apresentada? *

- ◯ Sim
- ◯ Não

Seguinte — Página 1 de 9 — Limpar formulário

Informação do participante

Nesta secção são apresentadas questões que visam conhecer os conhecimentos e caraterísticas do participante.

Idade *

Escolha a opção na qual a sua idade está inserida.

- ◯ 18-24
- ◯ 25-34
- ◯ 35-44
- ◯ 45-54
- ◯ 55-64
- ◯ 65+

Sexo *

- ◯ Feminino
- ◯ Masculino
- ◯ Prefiro não responder
- ◯ Outra: _____

Nível de Escolaridade *

Selecione o seu nível de escolaridade. Caso o seu não se encontre nas opções, introduza o seu nível de escolaridade.

- ◯ 2º ciclo do ensino básico
- ◯ 3º ciclo do ensino básico
- ◯ Ensino Secundário
- ◯ Licenciatura
- ◯ Mestrado
- ◯ Doutoramento
- ◯ Outra: _____

Costuma usar tecnologias (computador, smartphone) ? Se sim, costuma aceder a websites? *

- ◯ Sim
- ◯ Não

Tem conhecimentos na área da conservação e restauro, prévios a este questionário? *

- ◯ Sim
- ◯ Não

Tarefa 1

Tarefas relativas a Obra de Arte, Ponto de Análise e Equipamento

Passo 1

Como classifica a sua experiência a realizar o login na aplicação? *

	1	2	3	4	5	
Muito Difícil	◯	◯	◯	◯	◯	Muito Acessível

Passo 2

Como classifica a sua experiência na inserção de obras na aplicação? *

	1	2	3	4	5	
Muito Difícil	◯	◯	◯	◯	◯	Muito Acessível

Passo 3

Como classifica o processo de procura por uma obra na aplicação? *

	1	2	3	4	5	
Muito Difícil	◯	◯	◯	◯	◯	Muito Acessível

Passo 4
Caso não seja possível efetuar, passe para o passo 6.

Como classifica o processo de inserção da nova imagem/camada associado à obra de arte?

	1	2	3	4	5	
Muito Difícil	○	○	○	○	○	Muito Acessível

Passo 5

Como classifica o processo de mudar o fundo da obra de arte para a nova imagem inserida?

	1	2	3	4	5	
Muito Difícil	○	○	○	○	○	Muito Acessível

Sugestões
Caso tenha sugestões para algum dos passos realizados nesta secção.

A sua resposta

Continuação Tarefa 1

Passo 6

Como classifica o processo de associar um novo pdf à obra de arte? *

	1	2	3	4	5	
Muito Difícil	○	○	○	○	○	Muito Acessível

Passo 7

Como classifica o processo de visualização das informações do pdf inserido? *

	1	2	3	4	5	
Muito Difícil	○	○	○	○	○	Muito Acessível

Passo 8

Como classifica o processo de adicionar um novo ponto de análise à obra de arte? *

	1	2	3	4	5	
Muito Difícil	○	○	○	○	○	Muito Acessível

Passo 9

Como classifica o processo de selecionar e abrir a pagina de um ponto de análise? *

	1	2	3	4	5	
Muito Difícil	○	○	○	○	○	Muito Acessível

Passo 10

Como classifica o processo de adicionar um novo equipamento ao ponto de análise ? *

	1	2	3	4	5	
Muito Difícil	○	○	○	○	○	Muito Acessível

Passo 11

Como classifica o processo de edição da informação de um equipamento? *

	1	2	3	4	5	
Muito Difícil	○	○	○	○	○	Muito Acessível

Passo 12

Como classifica o processo de visualização da informação do equipamento após edição? *

	1	2	3	4	5	
Muito Difícil	○	○	○	○	○	Muito Acessível

Passo 13

Como classifica o processo de remover um equipamento do sistema? *

	1	2	3	4	5	
Muito Difícil	○	○	○	○	○	Muito Acessível

Sugestões
Caso tenha sugestões para facilitar os processos realizados dos passos 6 ao 13.

A sua resposta

Fim Tarefa 1

Continuação Tarefa 2

Passo 6

Como classifica o processo de adicionar um novo ponto (ponto **A**) de análise (que aceita pontos de análise "especial") à obra de arte? *

	1	2	3	4	5	
Muito Difícil	◯	◯	◯	◯	◯	Muito Acessível

Passo 7

Como classifica o processo de listagem de pontos de análise da obra de arte? *

	1	2	3	4	5	
Muito Difícil	◯	◯	◯	◯	◯	Muito Acessível

Passo 8

Como classifica o processo de adicionar um ponto de análise "especial"? *

	1	2	3	4	5	
Muito Difícil	◯	◯	◯	◯	◯	Muito Acessível

Passo 9

Como classifica o processo de selecionar a opção para ser possível ver os pontos de análise "especiais" associados a um ponto de análise? *

	1	2	3	4	5	
Muito Difícil	◯	◯	◯	◯	◯	Muito Acessível

Passo 10

Como classifica o processo de procurar o ponto de análise "especial" (ponto **B**) na listagem de pontos do ponto de análise (ponto **A**)? *

	1	2	3	4	5	
Muito Difícil	◯	◯	◯	◯	◯	Muito Acessível

Passo 11

Como classifica o processo de edição das informações de um ponto de análise? *

	1	2	3	4	5	
Muito Difícil	◯	◯	◯	◯	◯	Muito Acessível

Passo 12

Como classifica o processo de visualização da informação do ponto de análise após edição? *

	1	2	3	4	5	
Muito Difícil	◯	◯	◯	◯	◯	Muito Acessível

Passo 13

Como classifica o processo de remoção de um ponto de análise do sistema? *

	1	2	3	4	5	
Muito Difícil	◯	◯	◯	◯	◯	Muito Acessível

Sugestões.
Caso tenha sugestões para facilitar os processos realizados dos passos 6 ao 13.

A sua resposta

Fim Tarefa 2

Questões Finais

Esta é a ultima secção do questionário e contem algumas questões sobre o funcionamento geral da aplicação.

Conseguiu realizar todos (ou quase todos) os passos indicados no guião? *

- ◯ Sim
- ◯ Não

Se respondeu "Não" em cima, indique quais passos (e respetiva tarefa) teve bastante dificuldade em realizar.

A sua resposta

Indique o grau de dificuldade perante a utilização das ferramentas apresentadas. *

	1	2	3	4	5	
Muito Difícil	◯	◯	◯	◯	◯	Muito Acessível

Indique o grau de satisfação perante a utilização das ferramentas apresentadas. *

	1	2	3	4	5	
Pouco Satisfeito(a)	◯	◯	◯	◯	◯	Muito Satisfeito(a)

Alguma vez utilizou uma aplicação semelhante? Se sim, qual? *

A sua resposta

Comentários adicionais sobre as funcionalidades apresentadas

A sua resposta

Comentários adicionais sobre o design das funcionalidades apresentadas

A sua resposta

Anterior

Enviar

Página 9 de 9

Limpar formulário

Nunca envie palavras-passe através dos Google Forms