Journal of Universal Computer Science, vol. 27, no. 12 (2021), 1275-1299
submitted: 11/2/2021, accepted: 9/8/2021, appeared: 28/12/2021 *CC BY-ND 4.0*

Designing, Realizing, Running, and Evaluating Virtual Museum–a Survey on Innovative Concepts and Technologies

Nelson Baloian
(DCC, Department of Computer Science, University of Chile
https://orcid.org/0000-0003-1608-6454, nbaloian@dcc.uchile.cl)

Daniel Biella
(University of Duisburg-Essen, Germany
https://orcid.org/0000-0003-1028-226X, daniel.biella@uni-due.de)

Wolfram Luther
(University of Duisburg-Essen, Germany
https://orcid.org/0000-0002-1245-7628, wolfram.luther@uni-due.de)

José A. Pino
(DCC, Department of Computer Science, University of Chile
https://orcid.org/0000-0002-5835-988X, jpino@dcc.uchile.cl)

Daniel Sacher
(University of Duisburg-Essen, Germany
https://orcid.org/0000-0001-7361-2743, danielsacher84@gmail.com)

Abstract: This paper presents a survey of innovative concepts and technologies involved in virtual museums (ViM) that shows their advantages and disadvantages in comparison with physical museums. We describe important lessons learned during the creation of three major virtual museums between 2010 and 2020 with partners at universities from Armenia, Germany, and Chile. Based on their categories and features, we distinguish between content-, communication- and collaboration-centric museums with a special focus on learning and co-curation. We give an overview of a generative approach to ViMs using the ViMCOX metadata format, the curator software suite ViMEDEAS, and a comprehensive validation and verification management. Theoretical considerations include exhibition design and new room concepts, positioning objects in their context, artwork authenticity, digital instances and rights management, distributed items, private museum and universal access, immersion, and tour and interaction design for people of all ages. As a result, this survey identifies different approaches and advocates for stakeholders' collaboration throughout the life cycle in determining the ViM's direction and evolution, its concepts, collection type, and the technologies used with their requirements and evaluation methods. The paper ends with a brief perspective on the use of artificial intelligence in ViMs.

Keywords: Museum category, virtual reality, interaction, co-curation, generative approach, software and hardware support, evaluation, standardized metadata, ViMEDEAS, ViMCOX
Categories: H.5, J.5, L.1, L.3, L.6
DOI: 10.3897/jucs.77153

1 Introduction: Museums' Impact, Mission and Collection Types

Impact. Since 2002, the European Group on Museum Statistics [EGMUS, 20] has been gathering and editing museum data from 35 participating countries ordered by topic and year. Among 20,672 registered museums 5,766 were devoted to art, archaeology and history, 2,032 to science and technology or ethnology, and 8,898 to other collection types, i.e., complex museums with various collections, specialized museums, museum complexes, and outdoor museums. In total, more than 48,463 exhibitions and 659 million visits per annum were mentioned by EGMUS after evaluating the data sent by 35 countries for the period 2004 to 2019. Even bearing in mind that reporting by the countries was incomplete and spread over 16 years and that those statistics are but a fraction and a projection of their correspondence to numbers in the world as a whole, they enable us to assess the significance of the museum sector for education, information, leisure, and tourism. At the same time, most national museum associations have published their own extensive statistics, surveys, and conclusions (cf. [Netherlands Museum Association, 11]). Manageable ways of measuring success in art museums and mission-focused criteria were proposed in [Anderson, 2004].

Mission. Through a web survey, [Huvila, 14] interviewed 131 professionals on the common role of archives, libraries, and museums in contemporary society. The main finding of this study is, however, that the respondents lacked consensus on the essence of the future role of galleries, libraries, archives, and museums (GLAM) and especially on how to maintain, increase, and reassert it (→ scope, crowdsourcing).

In July 2012, the UK Museums Association published the *Museums 2020* discussion paper, which was based on a questionnaire asking 12 questions intended to gather views about how museums should change. Its goal was to guide the transformation process to focus on museums' potential and better fulfill their cultural, educational, societal, and environmental mission [Museums Association, 12].

The questions mainly concerned some of the museums categories and key concepts shown in Figure 1 and ways to increase their contribution to society and cultural life in order to augment the happiness, health, and wellbeing of individuals, to become more integral to communities, and to focus on museums' most important impacts. The organizers emphasized participatory aspects, e.g., to better "involve people in museum's exhibitions, programmes, and decision-making."

Nine months later, the Museums Association published a survey of the responses to *Museums 2020*. The organizers received 175 written responses from museums, sector organizations and individuals, which they evaluated, summarized, and displayed in 11 key points and a full report. There was particular support for community participation and co-creation issues. The museums' focus should be on how "to create an audience-led programme that considers audiences as both creators and consumers of knowledge," … "to address learning and participation as core activity," and to enable "collections [to] lead to wider, better and deeper audience engagement." [Museums Association, 13] (→ learning, participation).

The authors recognized that *Museums 2020* neglects some museum impacts and some areas of museum work. For example, the questions did not address the role of digitization, online exhibitions, ViMs, multiple instances of artwork, artificial intelligence (AI) or modern human-machine interfaces, issues that should be taken into account, as proposed by the Association of Independent Museums, to "Improve user experience as a seamless high quality offer, linking virtual and actual provision as a compelling 'must see' experience." (→ physicality vs virtuality)

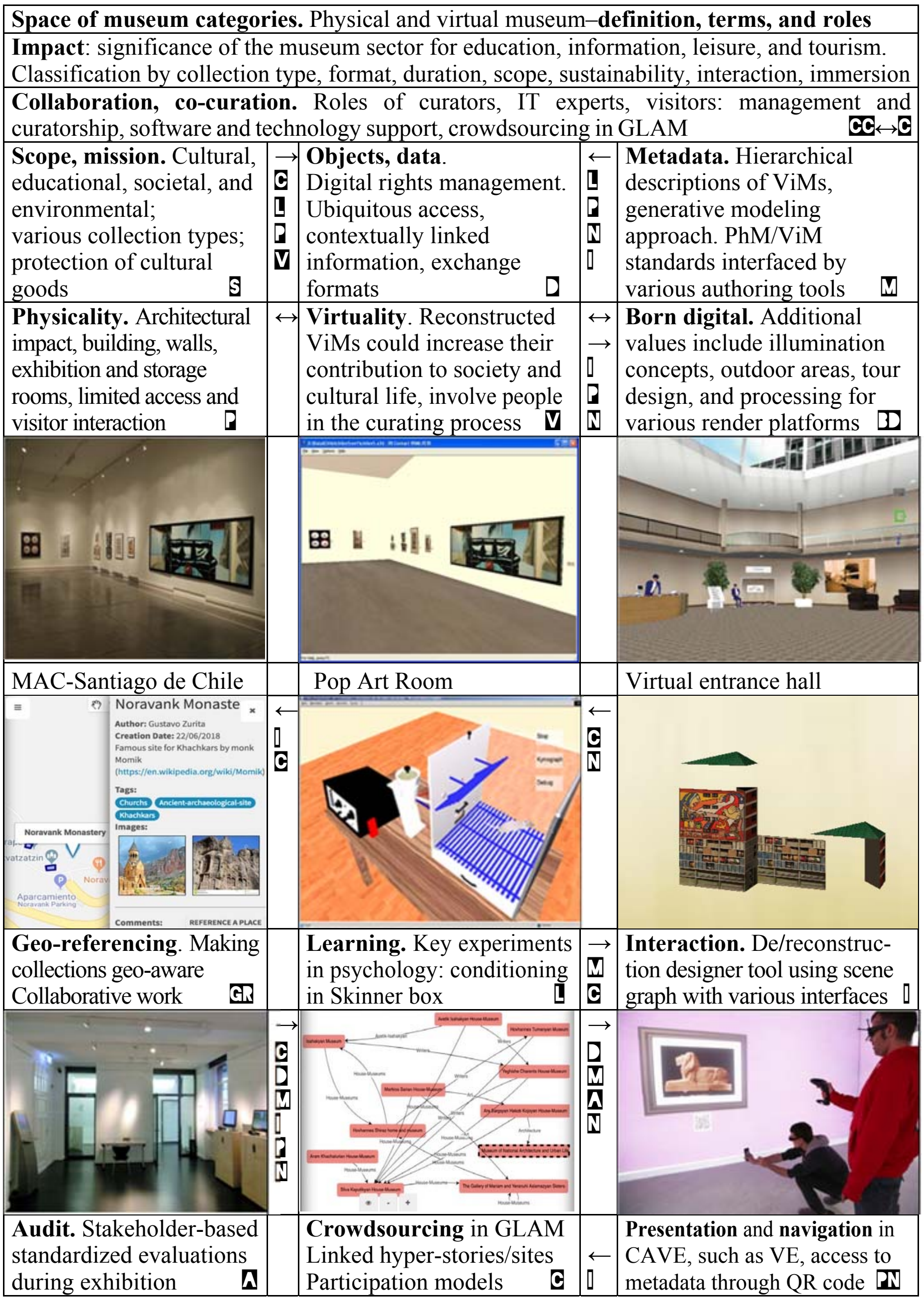

Figure 1: Museums and their scopes, categories and features. Use cases are documented on the SCG-website http://www.scg.inf.uni-due.de/abschlussarbeiten.php

The report shows a clear pleading for a change in museum self-image and culture, a move towards participation, creativity and inclusion of digital technology, new presentation and interaction approaches. To achieve the transformation process, we want to have a nearer look to the rich museum landscape, their collection types and requirements concerning software and hardware support, and interactive experiences.

Collection types. The Museum Property Handbook Department Manual, Part 411 (411 DM) set the overall policy for the management and preservation of museum property at the U.S. Department of the Interior. Content- or discipline-specific hierarchical classifications with type and subtype topics are provided as a suggested guideline for developing a bureau classification system: archeology, ethnography, history objects, art, biology, paleontology, geology, and environmental samples collections are categories of a museum property [MPH, 20, Appendix A] (→ scope).

[Szostak, 16] proposes an approach to subject classification, which establishes a list of typical attributes and requires access to controlled vocabularies. Many sources can be combined to this effect such as the Art and Architecture Thesaurus [Getty, 14] and Nomenclature [Bourcier, 15], which already provide hierarchically organized lists of the sorts of objects museums have to classify. These keyword-based classification lists can be supplemented by categorizing using verbs and adjectival/adverbial qualifiers (→ metadata). [Navarrete, 16] comments, “A metadata policy will help museums face the challenge to find their place in the new information space. Naturally, it would seem, the museum would serve as a node in a network connecting objects, information, people and places.” (→ geo-referencing).

This survey on virtual museums’ innovative concepts and technologies summarizes experiences with the design, generation, use, and evaluation of three important categories from the perspective of curators, visitors, and experts. Our insights were gained through virtual museum project realizations during a cooperation with the Museo de Arte Contemporaneo (MAC, Santiago de Chile), a reconstruction of the largely destroyed works of the German-Jewish sculptor Leopold Fleischhacker (LFM) and the Digitization of Khachkars (Armenian cross stones): Establishing a Virtual Museum in Armenia (DiKEViMA), projects inspired by volunteers and a large number of student theses. Khachkars incorporate carvings with wide frames and variously shaped crosses blended with sophisticated ornamentation.

We describe our work with ViMs and the participation of their stakeholders in terms of nine dimensions and compare the innovative significance of ViM in society with that of physical museums (PhM) and collections [Biella, 10; Sacher, 13; Baloian, 20]. Our generative approach is based on digitized and remodeled exhibit areas, high-quality 3D shapes, and the metadata of museum objects integrated into a cooperative workflow involving curators, visitors, and experts with tool support for design, modeling, realization, use, and dissemination. In section 2 we introduce important terms, definitions, and (virtual) museum categories and roles. Section 3 highlights the content-, communication-, and collaboration-centric LFM from the stakeholders’ point of view, deals with software and technology support, and resumes the workflow of a generative approach to ViM using the Virtual Museum and Cultural Object Exchange Format (ViMCOX metadata format) [Sacher, 17].

Section 4 is devoted to communication- and collaboration-centric ViMs and their new technologies. Section 5 quotes properties, discusses advantages and disadvantages of virtual and physical museums, and lists additional values of virtual museums concerning visitors and curators. Section 6 is devoted to metadata standards for (virtual) museums. Section 7 highlights user specific presentation modes, navigation support, and user-artifact interaction. Section 8 focuses on the role of co-curation in galleries, libraries, archives, and museums. Section 9 highlights the value of collaboration in ViMs when establishing, designing, planning, realizing, operating, deploying, and visiting a virtual exhibition.

Section 10 deals with geo-referencing and ubiquitous approach of the visitors to distributed artwork. Section 11 presents self-report questionnaires intended to accompany a team through the ViM realization process and is followed by our conclusions.

2 Virtual Museums: Definition, Types, Categories, and Dimensions

In the article "On the Origins of the Virtual Museum" [Huhtamo, 02], the author mentions important contributors, early descriptions, and initial realization in parallel with the emergence of the World Wide Web, hypertext, 3D modeling languages, browsers, and CD-based multimedia products conceived by leading museums as preparation for or a supplement to an on-site visit. The author sees the origin of the ViM and its additional value in relation to exhibition design, including new media and room concepts, one of the avant-garde art movements of the early 20th century. These ideas remain radical changes in the concept and roles of art and a thorough rethinking of the relationship between exhibition spaces, exhibits, and visitors, putting objects in their context, using lighting and animation, and integrating and activating the viewer (→ additional values).

Huhtamo successfully focuses on the design of ViMs by examining innovations they anticipate in the fields of exhibition design and interactive media art. He transfers historical challenges for stakeholders in ViM into a series of questions that even today have not lost their relevance. His questions mainly concern exhibition design, visitors' issues, and user-artwork interaction, addressing unusual perceptions of space, the loss of tactility in ViM (cf. Stockholm's Vasa Museum), and more generally, the relation between physical and ViMs (→ physical vs virtual museum).

The Virtual Museum Transitional Network [V-MUST, 14] provides state of the art examples for ViMs, a definition of the term *virtual museum*, and an initial hierarchical three tier classification system reflecting administrative, descriptive, technical, and use issues:

- Content: born digital content or reconstructions using 2D grabbing or 3D modeling. Collection type: art, cultural heritage and history; science and technology, ethnology and other collection types (→ scope, physical or virtual museum)
- Communication: descriptive, narrative, dramatization-based
- Format: distributed virtual reality (VR), ubiquitous accessibility (→ geo-positioning, ubiquitous approach, distributed items/visitors)
- Scope: education, entertainment, visitors' experience, promotional, research, gamification, learning …
- Duration: ViM is usable according to specific time intervals.
- Sustainability: accessibility, reusability, rescaling, portability, maintainability, and exchangeability

- Interaction technology: device-based, speech or gesture-based (→ interaction)
- Degrees of immersion in ViM and VE (virtual environments) (→ presentation)

In addition to ViM definitions provided by the International Council of Museums (ICOM) and V-MUST 2014, the ViMM Working Group 1.1—"What Is a Virtual Museum? Terms of Reference, Scope and Objectives"—created a list of relevant definitions and a list of ViMs for further discussion and suggested answers to the question raised. The terms and their definition are classified into various categories, with several types under each category [ViMM, 17].

[Sacher, 17] resumes the discussion in [Hazan, 14] with the following statement: "A Virtual Museum is a communication product made accessible by an institution to the public that is focused on tangible or intangible heritage. It typically uses interactivity and immersion for the purpose of education, research, enjoyment, and enhancement of visitor experience. Virtual Museums are usually, but not exclusively delivered electronically when they are denoted as online museums, hyper museum, digital museum, cyber museums that are related to Virtual Museum domain."

A recent comprehensive overview of the origins, concepts, and terminology of the ViM is provided in [Schweibenz, 19]. Designing, realizing and running a multidimensional ViM is reached in several stages [Baloian, 17] and is highlighted in section 3. In [Geser, 13] and [Sacher, 17] three (Vi)M categories are proposed. The category *content-centric* ViM (focusing on artwork and its setting) is superordinate to the other categories and of particular importance for virtual museums, since here—in addition to the content—its surroundings, rooms, and a logical floor plan with navigation elements must be designed and implemented. This leads, especially when real existing objects are digitized, to large data sets and their metadata.

In this context, the mathematical dimension concept for a Euclidean vector space with three space dimensions and one time dimension is used to allow event-based models, and further parameters for the surface shape and color, lighting, appearance and history of the artifact. Another conceptual category communication-centric ViM is about knowledge transfer, learning, linking to related objects, forms of presentation, navigation and interaction, standardized data and metadata exchange, the use of appropriate formats, interfaces and output devices.

The collaboration-centric ViM includes appropriate web platforms with shared workspaces and participatory approaches such as crowdsourcing and co-curation. Hyper-storytelling based on geo-referenced archaeological artifacts belongs to the last two categories. The concepts realized in these categories are often called ViM dimensions with a dimension definition from graph theory: the minimum number of vertices of an undirected graph G in a subset S of vertices such that all other vertices are uniquely determined by their distances to the vertices in S. Here, for the definition of the set S, all child nodes of the root can be selected; then further nodes may exist on a path down to leaf, which is the node with the largest distance corresponding to the complete implementation of the category with the subcategories or types. Along these paths, the ViM dimensions are then evaluated (cf. Figure 2) with respect to the annotated quality criteria. Rather than a graph visualization, a regular *n*-sided polygon could be used. If the feature associated with a node from S appears to be too general or comprehensive, it can be split into multiple nodes to increase the graph dimension.

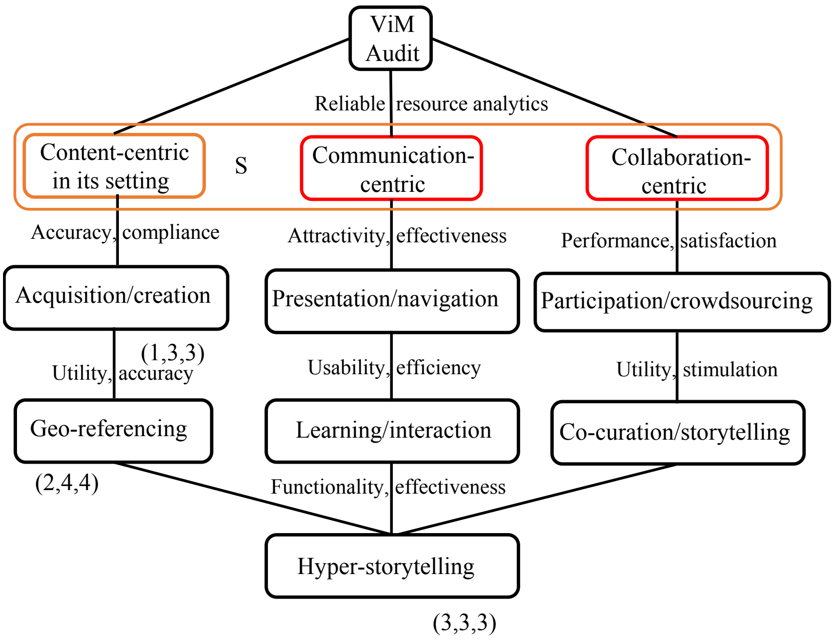

Figure 2: Auditing content-, communication-, and collaboration-centric ViM

3 LFM: A Content-, Communication-, and Collaboration-centric VM

Different skills and experiences are needed from people working on these different categories. Sacher's thesis [Sacher, 17] describes a full development cycle of a participatory museum with digital artwork guided by curators and art history experts. The showcase LFM presented on-site at the Düsseldorf memorial to the victims of persecution from November 10, 2015, to January 27, 2016, comprises the creation of exhibition space designs, digitization and 3D reconstruction, metadata enrichment, user interface design, VE creation, navigation aid, and tour design. Visitors can work with four versions of the LFM, each of which proposes another presentation mode, a different way to navigate through the exposition areas and various degrees of interaction.

Realization and running of a VM is reached in several stages: establishing, designing, "constructing, running, and operating a VM within its lifespan" [Baloian, 17]. Different skills and experience are needed from people working on these different phases. Main tasks concern museum management and curatorship, software and technology support, and user issues (cf. Figure 3). "The Epidat database developed and hosted by the Salomon Steinheim Institute (Essen) provides epigraphic information about Jewish tombstones, including descriptive information, inscriptions, and transcriptions," [Sacher, 13]. Additional features are actual documentation, digital rights, and a thorough evaluation management.

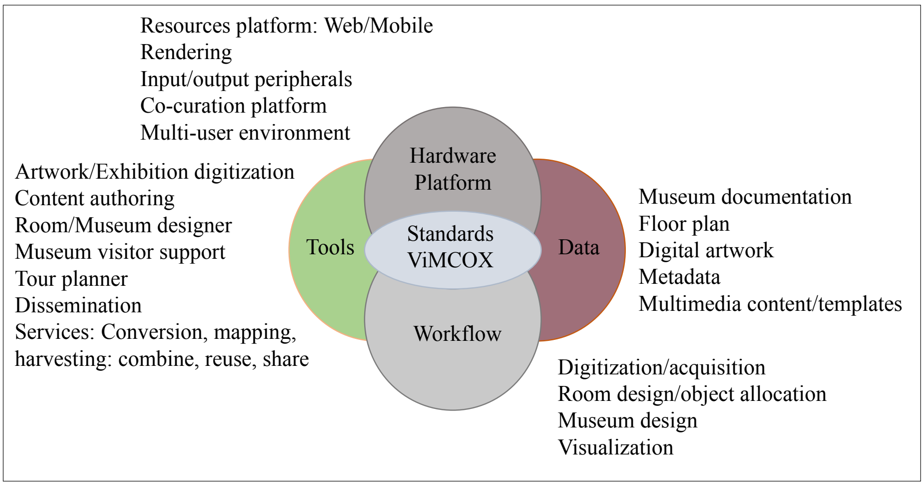

Figure 3: Museum software and technology support

The LFM stand-alone running installation serves as "proof of concept implementation and demonstrates content re-targeting for various input/output peripherals such as touch screens, gamepads, single projection systems, and Cave Automatic Virtual Environments (CAVE). Iterative testing, auditing of requirements and user-based evaluations" take place in the lab and on-site during an exhibition [Sacher, 17]. (→ audit, presentation).

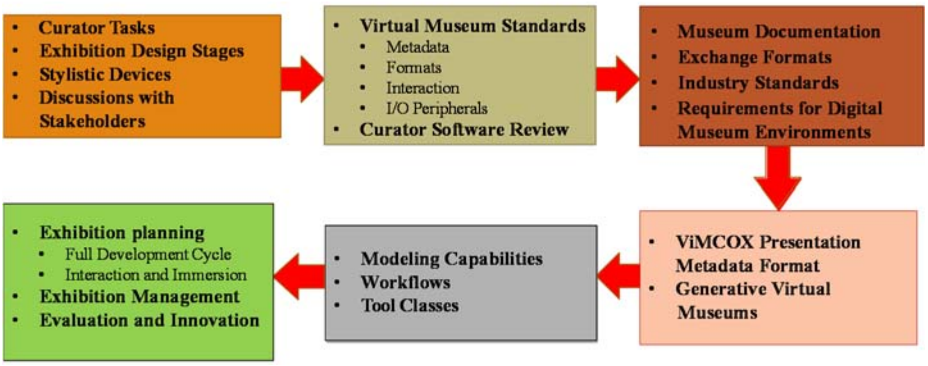

Figure 4: Workflow of a generative approach to ViM using a new metadata format

3.1 Generative Modeling Approach

This methodology uses a modular metadata-driven concept and relies on generative approaches to create 2D/3D content-based exhibition designs specified in the ViMCOX language (cf. Figure 4). ViMCOX was developed in order to provide a semantic structure for exhibits and complete museums (rooms, floors, building, walls, furniture, lighting, outdoor areas, etc.) [ViMCOX, 20]. "It combines community contributions to administrative and descriptive metadata with technical and usage metadata provided by the institution operating the museum" [Baloian, 17]. It is based on the formal generation of metadata instances describing virtual exhibitions using various construction parameters, content or search queries, and combinations of tailored authoring tools, i.e., floor planner, museum layout developer, exhibition and interactions designers (2D, 3D wysiwyg), mobile data acquisition (grabbing exhibition), and the underlying middleware (content connector, metadata mapper, generator, publisher).

ViMCOX metadata generation of complete ViMs further allows for re-targeting of virtual exhibitions for different rendering platforms or presentation systems. Tailored authoring tools can operate solely on metadata instead of implementing complex 3D rendering and authoring interfaces [Sacher, 13; Sacher, 17].

Main tasks concern museum management and curatorship, software and technology support, and user issues (cf. Figure 4).

Design aspects play an important role in the development process of virtual exhibition spaces, as stated in [Biella, 15]. The first contact with an unknown system occurs via standardized user interface icons and needs unambiguous symbols as metaphors for underlying functions or activities. Meaningful landmarks and connectors help users navigate and walk within the VEs to acquire information and start activities. "Metaphorical spatial design creates places where activities are carried out, paths leading to other places and domains, and semantic spaces consisting of several vantage points accessible by paths and separated from other domains by thresholds. Metaphorical temporal design allows the user to change from the (actual or historical) present to the past or the future." Contextual metaphors may concern a visitor's progress along a certain path (moving from viewpoint to viewpoint with a specific user interface). Conceptual metaphors with their semantic frames help in comprehending events, actions, activities, and states that are accessible in a certain room or context.

"Conceiving a multidimensional metaphorical space, the designer must guarantee spatial, temporal, contextual, and conceptual consistency, which can be realized using an architectural floor plan with simple room icons and an ordered sequence of viewpoints along a path that can be reached by point and click actions" as well as through a formally described task model [Biella, 15].

4 Collaboration- and Communication-centric Virtual Museums

Several case studies on ViMs serve as the basis of our considerations. We implemented ViMs and laboratories, which showed, in particular, how involving people in collaborative and crowdsourcing activities could transform museums/labs into participatory spaces [Biella, 16; Sacher, 17; Baloian, 20]. "The stakeholders concerned with the collaborative co-curation process take care of the coordination of group building, task allocation, motivation of team members, communication in the context of collaborative evaluation and testing, and knowledge generation and problem solving via information processing in the creating and visiting process of virtual exhibitions" [Baloian, 17] (→ co-curation). The authors propose the following stakeholders' classification, roles, and responsibilities:

Museum management and curatorship: Curators and museum staff

- manage the museum and its collections, administrating, documenting, preserving, displaying, archiving, and exchanging content;

- design and realize exhibitions (selection, metadata import, floor planning, layout, positioning, navigation support, publication);
- execute day-to-day operation, dealing with stakeholders.

Museum software and technology support:

Software architects, designer, developers, engineers and technicians

- design, develop, and maintain ViM and authoring tools;
- are responsible for data collection, metadata administration and dissemination, digitization and classification of artwork, 3D modeling, and realization of presentation platforms, providing immersive multimodal presence, interaction, and collaboration support;
- maintain hardware, and together with curators and visitors, establish valuation policy and innovation.

Visitors, experts, researchers, artists, and enthusiasts work together as contributors to the participatory museum. They use (virtual) museums for leisure, entertainment, or educational purposes, plan or reflect on visits with various activities, and contribute metadata and/or artwork (→ crowdsourcing and co-curation in GLAM).

Besides a comprehensive analysis of the relevant ViM literature, the post-doctoral thesis [Khundam, 19] reports on the development of an interactive storytelling platform and a template for including interactive content and various interaction devices via formal descriptions of devices, interactions, tasks, and action logic.

3D single-user interaction can be roughly classified into navigation (viewpoint manipulation), object selection and manipulation, and application control. This approach was extended to multi-hand and multi-user metaphors for interaction and collaboration in many directions. (→ navigation, collaboration)

Post Windows-Icons-Menus-Pointer interfaces provide a more natural way to communicate, select, manipulate, or transform objects—often directly—without interfering metaphors: Simultaneous speech and gesture input using gloves or acting directly in a CAVE-like environment; moving or navigating via a walk or fly metaphor; or geometric operations combining translation, rotation, and scaling executed with a virtual hand.

Selection and manipulation outside the area of reach is achieved with the ray-casting metaphor, which shoots a ray from the virtual hand into the scene to detect and select an object. Objects can be manipulated via an interactive elastic arm. Users grow or shrink themselves to achieve work on different scales.

In recent publications some emphasis is given to a new versatile 2D Pointer/3D Ray metaphor dedicated to non- or semi-immersive 3D interactions, which were tested in comparison with other solutions [Duval, 12]. Some of the 3D pointing and picking metaphors have already been defined and implemented in Java3D or 3D game engines (e.g., jMonkey, OGRE, Unity3D) (→ presentation and interaction).

[Sacher, 15] reports a use case based on the ViM metadata, the curator software suite *Virtual Museum Exhibition Designer Using Enhanced ARCO Standard* (ViMEDEAS), and its predecessor, the framework for the replication of experiments in VE (Replicave2), which generates a "content bundle and a VRML file, which is then passed to *Inside*, an extension of the ViSTA toolkit for interactive rendering in a CAVE. In this more interactive environment, visitors virtually walk through the ViM. Visitors are able to access supplementary material or comment/annotate exhibits by photographing Quick Response (QR) codes placed in direct proximity to each exhibit item."

To formatively assess the Khachkar Virtual Museum (KViM) realized with the Unity development platform in the DiKEViMA project, a preliminary usability/utility study was conducted concerning user navigation, missing and possible new features, and effectiveness in increasing users' interest and knowledge of objects related to cultural heritage in outdoor environments [Baloian, 19].

5 Physicality vs Virtuality

Classical and virtual museums and exhibitions have many things in common concerning their tasks, goals, the groups of people involved, and their interdisciplinary orientation and position in society. However, they also differ considerably in the phases of planning, creation, operation, dismantling, and storage; the expertise of the specialists; curatorial activities; handling of artworks and their owners; and exchange between the institutions. There are significant differences between the three groups of curators, experts, and visitors, especially with regard to their tasks, activities, duties, and relationship to the artifacts. Examples of parallel exhibits are explained and evaluated using a few examples combining artwork and their virtual instances in joint exhibitions [Lischke, 14].

[Marin-Morales, 19] describes significant similarities and differences in navigation in physical and virtual museums when using a head mounted device. Whereas classical as well as virtual museums are dependent on the input of artists, art historians, archivists, business economists, and journalists, computer scientists and computer and network specialists are now taking over the role of experts and replacing architects, civil engineers and craftsmen, forwarding agents, custodians, and supervisory personnel.

The expectations, duties and possibilities of the visitors are a priori different in each forms. The same applies to the sensory and motoric visitor experience, which, as already mentioned, differs in many ways. Further differences arise in the communication between visitors, the local and temporal organization of access to the exhibited works in their order, interaction with the items and additional information. Finally, effects on and significance for society have to be assessed in terms of education, leisure, and preservation of cultural heritage, which are fulfilled in varying ways and to varying degrees. Especially in our century of great challenges such as climate change, pandemics, migration and flight, digitalization, globalization, and the preservation of cultural identity, it is obvious that museums and collections have a special significance as peacemaking centers of engagement and participation.

5.1 Virtuality—Additional Values

As described in [Fuhrmann, 15], the European digital agenda prompts cultural institutions to promote digitization and online accessibility, thus, 2D digitization has been a core task for many years. Previously, due to the high financial and time investment, the focus of 3D digitization was prestigious individual artifacts rather than complete collections. Today, although 3D content acquisition is still a challenging task, large international museums and museum projects promote and support digitization initiatives for a variety of reasons and promote and offer open access to digital heritage materials. The reasons for this are certainly that exhibitions can be advertised in advance and are at least partially available after completion. The inventory is also virtualized for their protection and allows artwork and acquisitions kept in store rooms to be made accessible to the general audience both for the public sector and for government ministries and missions abroad.

ViMs may be an important supplement to physical collections. They propose new means of participation online or on-site, ubiquitous access even in times of pandemic, and cross-collection exhibitions, “contribute to the reconstitution and conservation of cultural heritage sites and offer opportunities to enrich on-site visits or help visitors prepare and reflect on physical museum visits. The whole process of establishing, designing, planning, realizing, and operating a ViM and visiting a virtual exhibition is currently only partly supported by appropriate software tools” [Sacher, 17]. ViMs are complex in their conceptual creation, digitization and virtualization, and platform maintenance and in the achievement of a visitor experience. Yet, they allow and even facilitate the protection of cultural goods and the democratization of access by overcoming space and time restrictions and providing links to additional artwork. According to requirements and interaction design, visitors participate, interact in 2D/3D or immersive virtual environments, and deconstruct and reconstruct items.

Design templates including rooms, walls, illumination, and outdoor areas simplify the generation. Access from any location without time or space limits, group-specific navigation, and interaction appropriate to age and interest is guaranteed or feasible. Artwork can be linked to metadata on demand, and information can be accessed almost without restriction. Transport and insurance costs and security for exhibition spaces and items are unnecessary, exhibition planning is carried out with digital support, exhibitions can be recorded and preserved, and stored artwork is available on request. Of course, it should not be overlooked that software and middleware must be rapidly adapted to innovations and version changes of online platforms.

6 Metadata and Standards Generating Virtual Museums

There are approximately 100 cultural heritage metadata standards available [Sacher, 17]. We list only the most important groups in the context of ViM and cite examples.

- ViM standards: ARCO, TourML, ViMCOX Virtual Museum and Cultural Object
- Virtual Environment formats: VIXEE, Contriga
- Architectural standards: CAD, IFC/BIM, CityGML/IndoorGML
- Educational metadata standards: IEEE Learning Object Model (→ learning)

LIDO (Lightweight Information Describing Objects) [LIDO, 10] is the successor of the metadata exchange format *museumdat*, which was inspired by CDWA Lite and SPECTRUM, is CIDOC CRM (Comité International pour la Documentation-Conceptual Reference Model) compliant, and can be used to document properties of all kinds of cultural heritage.

Work package 3 of the ATHENA project [McKenna, 09] deals with four important application questions in connection with metadata standards:

- Reviewing important categories of the standards in use by museums
- Mapping those standards to a common format and between two metadata standards

- Assessing the requirements for the persistent identification and differentiation of instances of digital objects and collections
- Tool support for the conversion of museum data into the common format.

In recent years, we have focused our development on the viable ViM metadata standard ViMCOX in the context of existing standards such as LIDO and the realization of the multipurpose system ViMEDEAS [ViMCOX, 20]. ViMEDEAS currently supports VRML, X3D and X3Dom, and backwards compatibility to VRML via XSL Transformations (XSLT). Smaller editors to design and generate virtual 3D and 2D museum environments or to publish and archive virtual exhibition layouts were developed in parallel. Metadata concerns the following attributes [Baloian, 20]:

- "Encoding for machine readability, data types, processing, communication, exchange, and storage
- Structuring/Classifying: categories, hierarchies, sets, elements, and relations; indexing, referencing, and linking with similar items
- Naming: headings, types, values, controlled vocabularies, metrics, multilingual support, (fuzzy) search, and retrieval support (ontologies) [Harpring, 10]
- Content: 3D scene graph modelling, texturing and lighting, assets, objects, identifiers and various attributes, connectors, and metaphorical design
- Presentation: various exhibition environments, user support, tour planning, navigation and co-curation support, interaction, publication, and knowledge creation."

ViMCOX was extensively used in our ViM projects LFM and DiKEViMA: Fleischhacker's pictorial estate was scanned and recorded as ViMCOX XML instances and has been, where applicable, enriched with additional descriptive metadata.

In [Baloian, 20], the authors propose some modifications to the classification scheme of khachkars' metadata introduced by [Khatchadourian, 14] in order to allow automatic segmentation on three levels. This approach enables the motifs on the front of a khachkar to be assigned to their classes: border structures, frames, crosses, geometric, vegetable, and figurative objects, as well as repeating patterns. An implementation proposal is described, but the realization is ongoing work.

7 Presentation, Navigation, and Interaction

Presentation of a ViM needs a transformation of the parametric 3D models into an object-oriented and extendable web representation and connects content and context with target groups. ViMCOX as a presentation format and modelling language encompasses the complete museum design such as room layouts, exhibit arrangement, lighting, and interaction with exhibit items. A formal description of presentation formats and templates is largely independent of user interface component, hardware/middleware platforms, and tool support. As is noted in [Sacher, 17], the presentation stage depicts the general deployment of ViMs and continues in user-oriented evaluation methods, export, and dissemination.

The contribution [Styliani, 09] discusses various types of ViM depending on presentation platforms, visualization techniques, and user interfaces, which provide intuitive content handling and an entertaining and educational experience. For the purpose of presentation in various formats 2D, 3D, VR, a standardized metadata format facilitates the enrichment of digital resources with additional descriptions, metadata, and supplementary material. In this sense, presentation is a realization of the various designs in the context of ViMs and their room and content organization using stylistic devices and media, multilingual text, image and video, and sound. The general metadata processing and presentation behavior is designed to support multimedia organization and rendering of metadata using presentation templates. Stylistic devices for ViMs are multi-storey buildings, rooms, (partition) walls with doors and windows, showcases and other assets, illumination, outdoor areas, etc.

The authors [Chittaro, 04] propose a novel navigation aid intended to allow users to easily locate objects and places inside largescale VEs. This feature exploits 3D arrows to point towards the objects and places the user is interested in. As a supplement to free exploration of a VR, tour planning is an important issue in VR and comprises the planning of PhM and ViM visits, navigation support in VEs, thematic content or art in context, filtered content, and the recovery, review and publication of tours. TourML is an XML metadata scheme for structuring museum tours with a focus on mobile devices and tour guides. It allows an existing viewpoint of a room to be bound to a tour stop or the use of disjoint viewpoints by specifying visitor's position and orientation. Displayed markings on paths or 3D mini-map support can be used to assist visitors while they explore the ViM. Different navigation modes, (walk, fly, point-and-click, examine: zooming, moving, panning), support by mobile technology (GPS, QR codes), or landmarks are used as navigation-aid metaphors, complemented by teleporter metaphors or 3D fly navigation to access other exhibition areas.

Interaction allows modification of the exhibit. As described in [Biella, 10 and 16], "geometric objects can be moved or rotated, superposed, scaled or modified, cloned, or made invisible". A typical example of our approach is to use an interaction metaphor such as the presentation behavior to bind/trigger viewpoints/animations when a visitor clicks an exhibit. "Scene graph–based languages support the deconstruction of an object into its various parts and, in a different way, even its reconstruction from its parts. Thus, visitors become creators of multiple new representations of an artwork."

An interaction type taxonomy for ViMs was defined in [Biella, 10]. By consolidating/grouping these definitions, four interaction modes can be identified:

- *Geometric modification*: moving, rotating, scaling an exhibition item. Using this feature, visitors can scrutinize an object from different vantage points.
- *Dynamic and animated object*: allowing the modification of the form/shape and visual appearance, de-construction into different parts, reconstruction from parts or assembly of new exhibits from various parts, starting/stopping a dynamic process/animation
- *Experiment*: parameterizing and executing interactive experiments
- *Environmental*: influencing the room shape, lighting, or appearance of an exhibit through the visitors' presence. With this feature, visitors become part of the exhibit.

Visitors navigate within the exposition by moving through different viewpoints or clicking inside an exhibit area, interact with artwork, comment on their impressions, and cite related work.

To integrate the visitors into a VE, various technologies are used for the authoring of the ViM. Transformation technologies and tools may deploy the content model into the VE, such as a CAVE. Here, users navigate in the museum and access metadata by scanning the exhibit's QR codes [Sacher, 15].

In order to further develop the coexistence of PhM and ViM, Shehade and Stylianou [Shehade, 20] “explore the practices, experiences, and perceptions of museum professionals related to the use of VR technology in museums, as well as the advantages and challenges of such technologies, by evaluating an in-depth analysis.”

8 Crowdsourcing and Co-curation in GLAM

Crowdsourcing and co-creation are major dimensions in the generation and operation of GLAM. The technologies available nowadays, such as smartphones and social networks, enable people to participate in various ways, roles, and activities. The main goal of this proposed dimension of ViMs is a taxonomy of the various subtasks in digital co-curation activities provided by the crowd or by engaged people involved in the project. This taxonomy makes it possible to identify necessary tool support and advice by curators, experts, and software engineers.

[Oomen, 11] “lists three major models of participation that are also suitable as a categorization of projects designed by professionals in the cultural heritage domain:” Members of the crowd contribute data in *contributory projects*; they contribute and analyze data, help refine project design, or disseminate findings in *collaborative projects*; and they contribute and work together in *co-created projects*. In [Zlodi 2013], the authors provide an overview of crowdsourcing approaches in GLAM using the collective intelligence in the cultural heritage domain. Key terms, concepts, and corresponding case studies are discussed in order to describe a framework for crowdsourcing projects within the heritage sector, various types of crowdsourcing initiatives are considered.

[Biella 16] emphasize the usefulness of strategic plans to create innovative spaces in GLAM for expanding public engagement and running formal and informal learning programmes for children and young people. GLAM contributes to lifelong learning via a variety of programs both in physical facilities and in virtual rooms [Oxford, 15] In [Biella, 16], the authors offer a short literature review and highlight relevant terms and activities in the field, e.g., curators’ support through crowdsourcing.

An adequate communication and co-curation platform is needed for publishing calls and for giving access to tutorials and software tools, guidance from experts, and interfaces for transferring and checking models, rights and metadata. Figure 5 [Biella, 16] shows the complete process concerning co-curation activities to build and enhance virtual exhibitions. Co-curating means

- “automatic generation of a specific call defining the task, the qualifications necessary to address the task, and input sheets to collect text, data, and metadata”;
- “access to special purpose digitizing and modelling software and communication facilities where questions may be asked or comments collected and saved”;
- creating artwork: crowdsourcing digital 3D models, 3D scanning and modelling;
- asking questions, writing emails, providing information via various communication channels, such as completing questionnaires, signing electronic guest books;
- visual objects can be inspected and scrutinized from various vantage points, and, when interaction is provided, a visitor can modify the exhibit or an object’s position, exposition, or appearance. (→ navigation and interaction)

In most cases, the artwork is copyrighted, and curators are requested to adopt a high quality DRM. The owners of an artwork must grant permission for the creation of digital 3D representations and their dissemination via the internet or a standalone system under certain conditions. This may be documented in various ways, such as watermarking the exhibit or displaying copyright information concerning limitations on use and propagation. The curator provides metadata and exposition layout, which are part of the copyright agreement.

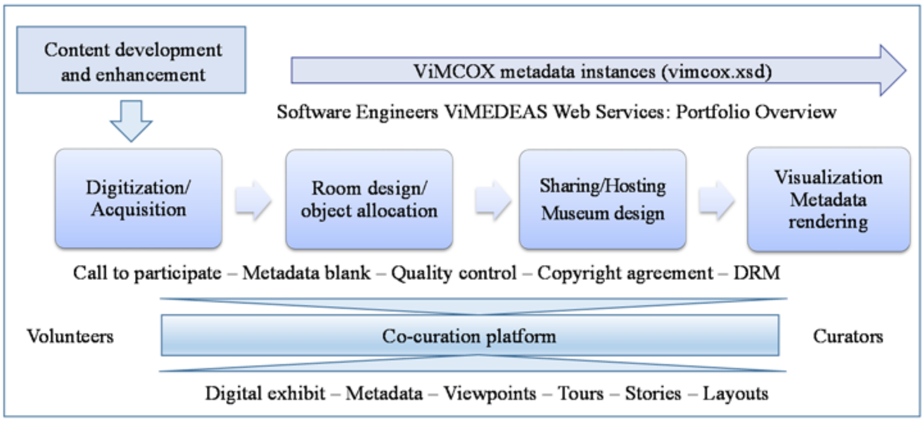

Figure 5: Participatory approach for creating, enhancing and disseminating ViMs

The software engineer organizes the creation of digital representations and their metadata, installs protection and builds a ViM, and volunteers and visitors, who are invited and encouraged to contribute to the exhibition, and must sign off on copyright agreements prohibiting abusive use and distribution of digital artwork [Sacher, 17].

As an alternative, leading museums abstain from watermarking and use the Open Archives Initiative (OAI) Protocol for Metadata Harvesting [OAI-PMH, 20]. The OAI is an organization that develops and applies technical interoperability standards that allow archives to share catalogue information (metadata) [Biella, 16].

9 Collaboration

“Virtual environments are valuable media for learning and experiencing the world. ViMs are non-location based, and they may be used for completely stand-alone exhibitions.” Moreover, they offer “a unique opportunity and provide additional tools for learning specific aspects of physical exhibitions. One of the important features of these systems is that they can provide collaborative opportunities for different types of visitors, thus making the observation or learning process engaging and effective” [Barbieri, 02].

The realization of a ViM occurs in several stages: establishing, designing, constructing, running, and operating a ViM within its lifespan. The main participants are curators, software engineers, and visitors, as well as sponsors/authorities, the crowd, museum enthusiasts, and special user groups such as instructors, architects, and experts.

"The stakeholders concerned in the collaborative co-curation process encompass the coordination of group building, task allocation, motivation of team members, communication in the context of collaborative evaluation and testing, knowledge generation, and problem solving via information processing in the creating and visiting process of virtual exhibitions." Members of such groups "are often distributed across a wide area; they constitute a multidisciplinary, multi-professional team. Individuals have various motivations and goals when working together. Co-curation in the generation process is paired with collaboration during a visit to an exhibition." [Sacher, 15] explains: "The generated data from collaboration can range from visitor's annotations or comments regarding specific exhibits up to complete exhibit models and room redesigns created in a VE. … Collaboration (in VEs) is implemented as users being co-located in the ViM, which enables information exchange and awareness of user actions via face-to-face communication." [Baloian, 17]

"In this paper the authors introduce two levels of collaboration: The collaborative work of promoters, curators, and intended users mainly concerns communication and co-ordination on Level 1, including motivation, goal, need, team building, task distribution, crowd participation, motivation, remuneration, evaluation planning, and further administrative tasks. Level 2 encompasses co-curation activities, including exhibition space design (designing ViM, expositions—spatial, metaphoric design, software tools, metadata acquisition, tour planning, interaction design), information processing (created, used, modified), and communication/interaction (various forms of communication and interaction among group members and between persons and items during the entire collaborative co-curation process)." These concepts are evaluated in our case studies LFM and DiKEViMA.

10 Ubiquitous Approach and Geo-positioning

ViMs today are a valuable supplement to classical museum exhibitions. They enable a new form of participation online or on-site, ubiquitous access, and cross-collection content. Virtual 3D museums contribute to the education and preservation of cultural heritage sites and make it possible to enrich on-site visits or help visitors prepare and reflect on real museum visits. The main innovation realized in the European Project IRMOS [Mazzetti, 11] is "the blend of virtual world with real world, geo-referencing real users through mobile phones GPS-enabled and mapping their avatar in the virtual world. Remote users will be able to virtually follow the visit of the on-site users and interact with them." As a further significant step is the activity tracker system for museum visitors presented in [Handojo, 19]. The system uses an Indoor Positioning System by utilizing Bluetooth Low Energy (BLE) beacons.

Inspired by the context of learning the cultural heritage of Armenian cross-stones, or khachkars, in the course of the DiKEViMA project, single or a group of khachkars could be geo-referenced in the place where the artifacts are currently located or were originally found. This can be done while the users are at the same place, using mobile computing devices with positioning capabilities, or remotely from a desktop computer.


```
<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<ns1:lidoWrap …xmlns:ns2=" "http://www.opengis.net/gml/3.2" xmlns:ns1=" http://www.lido-
schema.org/schema/v1.0/lido-v1.0.xsd ">
 <ns1:lido>
  <ns1:lidoRecID ns1:source="Armenia sacra" ns1:type="URL">http://editions.louvre.fr/en/titles/
```

```
            exhibition-catalogs/sites-countries/armenia-sacra.html</ns1:lidoRecID>
 <ns1:descriptiveMetadata xml:lang="en">
            ..............
  <ns1:objectIdentificationWrap>
             .........
    <ns1:repositoryWrap>
               ..........
        <ns1:repositorySet ns1:type="current">
               .........
           <ns1:repositoryLocation>
              <ns1:partOfPlace>
                  <ns1:namePlaceSet>
                       <ns1:appellationValue> Amaghu Valley, Vayots Dzor Province, Armenia
                       </ns1:appellationValue>
                  </ns1:namePlaceSet>
                  <ns1:gml>
                       <ns2:Point>
                           <ns2:coordinates>39.684061 45.232872 </ns2:coordinates>
                       </ns2:Point>
                  </ns1:gml>
              </ns1:partOfPlace>
              <ns1:partOfPlace>
                  <ns1:placeID ns1:type="Geo location" ns1:source="TGN">7024040</ns1:placeID>
                       <ns1:namePlaceSet>
                          <ns1:appellationValue>Vayots' Dzor province</ns1:appellationValue>
                       </ns1:namePlaceSet>
                    <ns1:gml>
                       <ns2:Point>
                          <ns2:coordinates>39.684972 45.232695</ns2:coordinates>
                       </ns2:Point>
                    </ns1:gml>
               </ns1:partOfPlace>
           </ns1:repositoryLocation>
        </ns1:repositorySet>
    </ns1:repositoryWrap>
    ........
 </ns1:lido>
</ns1:lidoWrap>
```


Figure 6: P'alik's khachkar from Norawank monastery; excerpt from metadata

As an application, users can also describe intangible heritage objects associated with specific geographical places. Hyperlinking co-curated and virtual 3D resources can both raise the awareness of mobile users about the existence of virtual replicas of intangible objects and provide access to these resources [Baloian, 19]. The listing in Figure 6 is an excerpt from the complete metadata in ViMCOX-LIDO XML format of P'alik's khachkar located at Amaghu Valley, Vayodz Dzor Province, Armenia [ViMEDEAS, 20].

11 Audit: Quality Management and Evaluation

Requirements engineering, iterative testing, requirements auditing, and final usability evaluation are carried out both in the development phase and in current exhibitions online or in a museum or comparable location. Evaluation aspects can be considered from the vantage points of curators, software engineers, the general public, engaged volunteers, and researchers involved in the development and use of ViMs with a focus on their individual needs. The presented evaluation methodology comprises initial interviews with curators regarding museum and exhibition design, developer tests (walk through reviews, flow/state charts, stress tests, copyright protection and safeguarding), user experience (UX) tests (utility, learnability and stimulation) in the lab with domain experts and a final on-site evaluation in a real application scenario to observe visitors' interaction with the system. To structure our approach, the evaluation is described analogously to the framework presented in [Antunes, 12]. The procedure from the LFM project is presented in [Auer, 18] and can be directly adopted for comparable ViM realizations.

Prior to the start of the project, a preliminary questionnaire is developed within a knowledge-based evaluation setting. Partitioned into several sections, it helps identify type, scope, and format of ViM, goals for all the parties involved and gathers relevant information about resource platform, content templates, room and floor design, digitization, metadata techniques, and interoperability standards to be used in the field, as well as possible usage scenarios for creating or using ViM curator tools.

After realization of a prototypical ViM, "a further knowledge- and rule-based evaluation focuses on model quality, deals with software stability in accordance with either the ISO/IEC 25010:2011 or the ISO/IEC/IEEE 29119 norm; failure-free system operation over a specified time; stress tests for fluent navigation, interaction, and display; error report; and confirmation of complete and correct realization of the curator's content specifications." Important quality criteria are accuracy, performance, and utility. Accuracy means in this context that data used or provided are correctly expressed by the chosen data types, fidelity of generation, structural or content integrity, and consistency (i.e. their logical relationship is preserved under processing). Fidelity measures the degree of similarity between museum items and their virtual instances with respect to appearance, size, color, and shape resp. form. The assessment of this criterion needs a reference or guaranteed error bounds, that is, calibration. Performance is a generic term for successful task completion and includes efficiency and effectiveness. Efficiency rates resource consumption in terms of time or cost; effectiveness assesses task completion. Fitness/utility assesses the number of resources and whether they address the user's needs.

"Another survey designed as an interview with targeted questions provides use cases including free and guided navigation through the exhibition rooms and outdoor area exhibition. It focuses on design flaws, subjective increase in knowledge, overall acceptance of ViMs, and visual fidelity/quality. A heterogeneous visitor group is interviewed to gather feedback from information technology and virtual reality specialists, art history experts, average museum visitors, and computer-savvy users.

The usability concept, co-curation contributions by the crowd, and support by curators and software engineers should be examined during an exhibition," [Auer, 18]. Questions may focus on room layout, technical equipment, and user introduction to the installations and their use. Important topics to include are interaction design, opportunities, and navigation support. Moving to the next viewpoint, visitors should select the nearest object or change rooms in the ViM using point-and-click operations or well-known teleporter metaphors [Auer, 20].

Another questionnaire should concern co-curation activities for volunteers to know: firstly, whether the taxonomy of proposed activities is meaningful and, secondly, which of the relevant activities is likely to be chosen or discarded by a particular visitor group. Further questions concern crowd's contributions to the ongoing exposition and publication of a tour, viewpoints or information about the artwork, and users' potential need for support from curators and software engineers (cf. Baloian, 17]). And finally the further development of the museum in the change of the requirements under consideration of technical progress is to be examined.

Now, our general quality criteria and metrics for the mission of museums and visitor experiences will be highlighted. The quality criteria and metrics given are partly used in our projects and described in greater detail in the sources cited. Quantitative data are mean values over a given period of time, tasks are specified according to visitor group, scope and difficulty. Table 1 provides an overview of common metrics [Anderson, 04], [Bertacchini, 11], [Gockel, 13], [Weyers, 19], [Auer, 20; Auer, 22].

User experience: Utility	**Performance Efficiency**	**Usability Learnability**	**Stimulation Perception**
Ratio of number of useful features/ functions to number of required features	Ratio of time used to total time spent completing tasks	Targeted survey to evaluate available functionalities in free navigation and guided tours, or ease of use Mean time to complete tasks as a function of trial	Measurement of cognitive, emotional, and sensory responses in the use of the VR functionalities (EEG, survey)

Mission and impact of ViM: Utility	**Performance Efficiency**	**Innovation power**	**Stimulation Attractivity**
Assessment of the extent to which the expectations of various visitor groups are met within the frame-work of institutional tasks and goals using surveys Evaluation of the social impact and success of ViMs activities or the ful-fillment of the ViM's inherent public mission.	Number of visitors Number and duration of exhibitions Scope and quality of the exhibits Institutional reputation Interoperability: extent of internal exchange and reuse of licensed content and (me-ta-)data, or external exchange across other services and institutions. [Sacher,17]	Quantity and extent of new concepts and technologies that enhance the core competencies of the institution and its performance in key dimensions: Visitor support and participation, ease of use, and sustainability.	Attraction power Average time spent in front of important items Increasing revenue through higher-profile exhibitions and visitors, providing and sharing content with other institutions.

Table 1: Metrics to validate common quality criteria for visitor experience, mission, and impact of ViM

12 Conclusions and Further Work

Digitization is the key issue of virtual museums and cultural collections and has revolutionized the quality and quantity of artworks available: Artworks and their digital instances can be quickly located, tagged with metadata and copyright information, shared, compared, and explored by visitors. Design, realization, and operation of ViM in relation with PhM and their stakeholders depends on many closely intertwined dimensions. Presentation platforms and toolboxes are based on generative approaches in conjunction with declarative modeling languages and provide templates, including exhibition and media rooms with variable floor plans, furniture and connectors between different areas, as well as readymade metadata forms with various object and space parameters. Methodical approaches to the various concepts and features support the overall process from the perspective of the participating curators, software developers, and visitors. Toolboxes and standardized metadata enable the efficient creation of ViMs from parameterized templates using objects and surrounding data obtained with image and object acquisition tools or provided by public institutions and the crowd.

Nevertheless, it cannot be ignored that there is no consistent design and tool support for the automatic capture of physical objects, artwork, or real exhibitions using photogrammetry and mobile devices; the automatic classification of objects with AI methods; or the support of generative approaches through visual editing. The same applies to XML schema language support for LIDO-ViMCOX-compliant descriptions and the provision of stable rendering environments with rich 3D modeling languages (Web-GL) in combination with classical programming languages such as Java and its architectures, even if major international projects show great progress towards these goals.

Technological innovations such as AI signify new cross-cutting concepts and are used for asset classification and cataloguing, data retrieval, and matching, visitor support, and learning resources. Their use in museums with a technology reference and interactive sensory- or action-based artworks is indispensable. To improve user experience in self-guided visits, chatbots automate communication and robots serve as museum guides with various purposes, such as interacting with visitors, answering questions, and telling stories [Duguleana, 20]. However, comparative evaluation is needed. A sensory-based, risk-aware ViM is presented in [Weyers, 16], [Auer, 22].

Acknowledgements

We would like to express our gratitude to all those involved in the aforementioned museum projects and to thank our anonymous reviewers for their helpful comments and suggestions, which greatly contributed to the clarity of the text.

References

[Anderson, 04] Anderson, M. L.: Metrics of Success in Art Museums. J. Paul Getty Trust, 1200 Getty Center Drive, Los Angeles, CA, USA, 2004, 20p.

[Antunes, 12] Antunes, P., Herskovic, V., Ochoa, S., Pino, J. A.: Structuring Dimensions for Collaborative Systems Evaluation. ACM Computing Surveys 44 (2), Article 8, 2012, 28p.

[Auer, 18] Auer, E., Luther, W.: Towards Human-Centered Paradigms in Verification and Validation Assessments, in Hajian, A. et al. (eds.): Collaborative Technologies and Data Science in Smart City Applications. Logos, Berlin, 2018, 68-81

[Auer, 20] Auer, E., Luther W., Weyers, B.: Reliable Visual Analytics, a Prerequisite for Outcome Assessment of Engineering Systems. Act Cybernetic 24 (3), 2020, 287-314

[Auer, 22] Auer, E., Luther, W..: Feature-oriented Digital Twins based on Reliable Museum Analytics during Life Cycle Phases, submitted to ISRERM 2022

[Baloian, 17] Baloian, N., Luther, W., Biella, D., Karapetyan, N., Pino, José A., Schreck, T., Hitschfeld, N.: Exploring Collaboration in the Realm of Virtual Museums, in Gutwin, C., Ochoa S., Vassileva, J., Inoue, T. (eds.): Collaboration and Technology. Proc. CRIWG 2017, LNCS 10391, Springer, 2017, 252-259

[Baloian, 19] Baloian, N., Zurita, G., Pino, J. A., Peñafiel, S., and Luther, W.: Developing Hyperstories in the Context of Cultural Heritage Appreciation, in Nakanishi, H. et al (Eds.): Collaboration Technologies and Social Computing, Proc. 25th Int. Conf., CRIWG + CollabTech 2019 Kyoto, Japan, Sept. 4–6, LNCS 11677, Springer, 2019, 110-128

[Baloian, 20] Baloian, N., Biella, D., Luther, W., Panay, B., Peñafiel, A., Pino, J. A.: Armenian Khachkars: Towards an Automated Handling of Segmentation and Classification, in Hajian, A. Baloian, N., Inoue, T., Luther, W. (eds.): Proc. 2nd CODASSCA Workshop Yerevan, Armenia, Sept. 14-17, Logos-Verlag, Berlin, 2020, 1-11

[Barbieri, 02] Barbieri, T., Paolini, P.: Cooperation Metaphors for Virtual Museums. Museums and the Web 2001, Archives & Museum Informatics, Pittsburgh, PA, 2001, 115–126

[Bertacchini, 11] Bertacchini, E. and Morando, F.: The Future of Museums in the Digital Age: New Models of Access and Use of Digital Collections. Working paper No. 5/2011, University of Turin, 2011

[Biella, 10] Biella, D., Luther, W., and Baloian, N.: Virtual Museum Exhibition Designer Using Enhanced ARCO Standard, in XXIX Int. Conf. SCCC, IEEE, 2010, 226-235

[Biella, 15] Biella, D., Sacher, D., Weyers, B., Luther, W., and Baloian, N.: Metaphorical Design of Virtual Museums and Laboratories: First Insights. 9th International Conference, UCAmI, Puerto Varas, Chile, December 1-4, 2015. LNCS 9454 Springer, 2015, 427-438

[Biella, 16] Biella, D., Pilz, T., Sacher, D., Weyers, B., Luther, W., Baloian, N., Schreck, T.: Crowdsourcing and Co-curation in Virtual Museums. Special Issue CRIWG 2015, JUCS 22 (10), 2016, 1277-1297

[Bourcier, 15] Bourcier, P., Dunn H., (and the Nomenclature Task Force): Nomenclature 4.0 for Museum Cataloging is an updated and expanded edition of Robert G. Chenhall's System for Classifying Man-Made Objects. American Association for State and Local History, 2015. http://resource.aaslh.org/view/nomenclature-4-0-for-museum-cataloing/#sthash.YBBObKfp.pdf

[Chittaro, 04] Chittaro, L., Burigat, S.: 3D Location-pointing as a Navigation Aid in Virtual Environments, in Proceedings of the Working Conference on Advanced Visual Interfaces. ACM New York, USA, 2004, 267-274

[Duval, 12] Duval, T.: Models for Design, Implementation and Deployment of 3D Collaborative Virtual Environments. Université Rennes 1, 2012

[Duguleana, 20] Duguleana, M., Briciu, V.-A., Duduman, I.-A., and Machidon, O. M.: A Virtual Assistant for Natural Interactions in Museums. Sustainability 12, 2020, 12, 6958

[EGMUS, 20] EGMUS Statistics: https://www.egmus.eu/

[Europeana, 15] Europeana Cloud Deliverable 1.3 User Requirements Analysis and Case Studies Report. Content Strategy Report. https://pro.europeana.eu/files/Europeana_Professional/Projects/Project_list/Europeana_Cloud/Deliverables/D1.3%20D1.6%20User%20Requirements%20Analysis%20and%20Case%20Studies%20Report%20Content%20Strategy%20Report.pdf

[Fuhrmann, 15] Fuhrmann, C., Santos, P., and Fellner, W.-D.: 3D-Massendigitalisie¬rung-ein Meilenstein für die museale Nutzung. Museumskunde 80, 2015, 58-61

[Geser, 13] Geser, G. and Niccolucci, F.: Virtual Museums, Digital Reference Collections and E-science Environments. Uncommon Culture, 3(5/6) 2013, 37p.

[Getty, 14] Getty Research Institute: Getty Vocabularies http://www.getty.edu/research/publications/electronic_publications/intro_controlled_vocab/cultural_objects.pdf

[Gockel, 13] Gockel, B., Graf, H., Pagano, A., Pescarin, S., and Eriksson, J.: ViMUXE, An Approach to User Experience Evaluation for Virtual Museums, in Marcus, A. (Ed.): Design, User Experience, and Usability. Design Philosophy, Methods, and Tools, LNCS 8012, Springer, 2013, 262-272

[Handojo, 19] Handojo, A., Lim, R., Octavia, T., and Anggita, J. K.: Museum Visitor Activity Tracker Using Indoor Positioning System. 4th Technology Innovation Management and Engineering Science International Conference (TIMES-iCON), Bangkok, Thailand, 2019, 1-5

[Harpring, 10] Harpring, P.: Introduction to Controlled Vocabularies: Terminologies for Art, Architecture, and Other with a foreword by Murtha Baca, 2010, 258 p.
Online http://www.getty.edu/publications/virtuallibrary/160606018X.html

[Hazan, 14] Hazan, S., Hermon, S.: On Defining the Virtual Museum: A V-MUST Research Project. In Electronic Imaging & the Visual Arts, Firenze University Press, 2014, 30-35

[Huhtamo, 02] Huhtamo, E.: On the Origins of the Virtual Museum, in Ross, P. (ed.): Museums in a Digital Age. Routledge, London, 2010, 121-135

[Huvila, 14] Huvila, I.: Archives, Libraries and Museums in the Contemporary Society: Perspectives of the Professionals. Proceedings iConference, 2014, 45-64

[Khatchadourian, 14] Khatchadourian, H., and Basmadijan, M.: L'art des khachkars: Les pierres à croix arméniennes d'Ispahan et de Jérusalem. Geuthner, Paris, 2014

[Khundam, 19] Khundam, Ch.: Evaluation of the Virtual Reality Usage for the Promotion of Historical Heritage. Université Grenoble, 2019. https://tel.archives-ouvertes.fr/tel-02165041

[LIDO, 10] LIDO Lightweight Information Describing Objects, Specification Version 1.0
http://www.lido-schema.org/schema/v1.0/lido-v1.0-specification.pdf
http://www.getty.edu/research/publications/electronic_publications/intro_controlled_vocab/cultural_objects.pdf

[Lischke, 14] Lischke, L., Dingler, T., Schneegaß, S., Schmidt, A.; van der Vaart, M. J., Wozniak, P.: Parallel Exhibits: Combining Physical and Virtual Exhibits. Proc. Engaging Spaces: Interpretation, Design and Digital Strategies: Dec. 1-3, 2014, Warsaw, Poland, 2014
https://pure.uva.nl/ws/files/2192095/154035_parallel_exhibits_nodem.pdf

[Marin-Morales, 19] Marín-Morales, J. et al.: Navigation Comparison between a Real and a Virtual Museum: Time-dependent Differences Using a Head Mounted Display. Interacting with Computers, 31 (2), 2019, 208–220

[Mazzetti, 11] Mazzetti, A.: Virtual Cities of art and Immersive Experience in Geo-Referenced Communities.
https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.174.2239&rep=rep1&type=pdf

[McKenna, 09] McKenna, G., De Loof, Ch.: Report on Existing Standards Applied in European Museums D3.1 2009. www.athenaeurope.eu

[Museums Association, 12] The Museums 2020 discussion paper. London, UK
https://www.museumsassociation.org/app/uploads/2020/06/24072012-discussion-paper.pdf

[Museums Association, 13] Responses to Museums 2020 Consultation. London, UK https://www.museumsassociation.org/campaigns/museums-change-lives/

[MPH, 20] Museum property handbook, Vol. I: Preservation and Protection of Museum Property, Vol. II: Documentation of Museum Property. U.S. Department of the Interior, 1849 C Street NW, Washington, DC 20240 https://www.doi.gov/museum/policy/DOI-Handbooks

[Navarrete, 16] Navarrete, T., Owen, J. M.: The Museum as Information Space: Metadata and Documentation, in Cultural Heritage in a Changing World. Springer, 2016, 111-123

[Netherlands Museum Association, 11] The Social Significance of Museums: More Than Worth It. April 2011 https://museumvereniging.nl/media/nmv_more_than_worth_it.pdf

[OAI-PhMH, 20] Open Archives Initiative Protocol for Metadata Harvesting https://www.openarchives.org/pmh/

[Oomen, 11] Oomen, J., Aroyo, L.: Crowdsourcing in the Cultural Heritage Domain: Opportunities and Challenges"; C&T '11 Proc. 5th Int. Conf. on Communities and Technologies, ACM New York, NY, 2011, 138-149

[Oxford, 15] GLAM Strategy Plan 2015-2020. https://www.glam.ox.ac.uk/strategic-plan

[Sacher, 13] Sacher, D., Brocke, M., Heitmann, M., Kaufhold, B., Luther, W., and Biella, D.: The Virtual Leopold Fleischhacker Museum MW2013: Museums and the Web 2013, April 17-20, Portland, OR, USA https://mw2013.museumsandtheweb.com/paper/the-virtual-leopold-fleischhacker-museum/

[Sacher, 15] Sacher, D., Weyers, B., Kuhlen, T. W., and Luther, W.: An Integrative Tool Chain for Collaborative Virtual Museums in Immersive Virtual Environments. Collaboration and Technology. 21st Int. Conf., CRIWG 2015, Springer, 2015, 86–94

[Sacher, 17] Sacher, D.: A Generative Approach to Virtual Museums Using a New Metadata Format: A Curators', Visitors' and Software Engineers' Perspective. PhD dissertation, University of Duisburg-Essen, 2017

[Shehade, 20] Shehade, M., Stylianou-Lambert, Th.: Virtual Reality in Museums: Exploring the Experiences of Museum Professionals. Appl. Sci. 10, 2020, 4031; doi:10.3390/app10114031

[Schweibenz, 19] Schweibenz, W.: The Virtual Museum: An Overview of Its Origins, Concepts, and Terminology. The Museum Review 4 (1), 2019, 1-35

[Styliani, 09] Styliani, S., Fotis, L., Kostas, K., and Petros, P.: Virtual Museums, a Survey and Some Issues for Consideration. Journal of Cultural Heritage 10 (4), 2009, 520 – 528

[Szostak, 16] Szostak, R.: Synthetic Classification of Museum Artifacts Using Basic Concepts. MW2016: Museums and the Web 2016. January 24, 2016 https://mw2016.museumsandtheweb.com/paper/synthetic-classification-of-museum-artifacts-using-basic-concepts/

[ViMCOX, 20] Virtual Museum and Cultural Object Exchange Format http://www.vimedeas.com/wordpress/?page_id=12

[ViMEDEAS, 20] Virtual Museum Exhibition Designer Using Enhanced ARCO Standard: Show Cases, Cooperations, DiKEViMA http://www.vimedeas.com/wordpress/

[ViMM, 17] ViMM Working group 1.1. What Is a Virtual Museum? https://www.vi-mm.eu/ http://www.vi-mm.eu/2017/03/21/working-group-1-1-what-is-a-virtual-museum/

[V-MUST, 14] V-Must.net - D 2.1c M21 2014 Terminology, Definitions and Types for Virtual Museums WP 2 Version 2.1c
http://www.v-must.net/sites/default/files/D2.1c%20V_Must_TERMINOLOGY_V2014_FINAL.pdf

[Weyers, 16] Weyers, B., Luther, W.: Risk Communication and Perception in Low- and High-Immersion Virtual Environments, in H.W. Huang et al. (editors): Proceedings APSSRA6 28-30 May 2016, Shanghai, China, 6p.

[Weyers, 19] Weyers, B., Auer, E., Luther, W.: The Role of Verification and Validation Techniques within Visual Analytics. JUCS 25 (8), 2019, 967-987

[Zlodi, 13] Zlodi, G., Ivanjko, T.: Crowdsourcing Digital Cultural Heritage. INFuture2013: Information Governance (1847-8220) 4, 2013, 199-207