virtual worlds

MDPI

Article

The Gaia System: Revolutionizing Museum Storytelling with Projection Mapping

Costas Boletsis * and Ophelia Prillard

SINTEF Digital, 0373 Oslo, Norway; ophelia.prillard@sintef.no
* Correspondence: konstantinos.boletsis@sintef.no

Abstract

The Gaia System is a tabletop projection mapping system for museum exhibitions, now in its third iteration and installed at the Sortland Museum (Norway). It presents socio-economic, environmental, and historical topics through an interactive spatial display. The system supports both multi-user interaction—allowing many visitors to engage simultaneously—and a tour guide mode for staff-led presentations. It combines scientific, data-driven visualizations with popular-science, story-driven content and integrates both real-time and locally stored data streams. Its design and development processes are thoroughly described. A field study with 32 participants yielded a System Usability Scale (SUS) score of 84.14 and a mean User Experience Questionnaire (UEQ-S) overall score of 1.93, indicating high usability and a positive user experience. The participants found the projection technology impressive and the content informative while noting challenges such as information overload, unclear temporal structuring of the content, and minor technical issues. Planned developments focus on restructuring the content for shorter sessions, implementing a new content management system, and refining the technical stability. Finally, this work reframes projection mapping as operational infrastructure rather than a fixed display, offering practical guidance for researchers advancing PM methodologies and museum practitioners deploying innovative, technology-driven exhibitions.

Keywords: augmented reality; human–computer interaction; projection mapping; museum

check for updates

Academic Editor: Rosario Schiano Lo Moriello

Received: 1 October 2025
Revised: 22 October 2025
Accepted: 23 October 2025
Published: 30 October 2025

Citation: Boletsis, C.; Prillard, O. The Gaia System: Revolutionizing Museum Storytelling with Projection Mapping. *Virtual Worlds* **2025**, *4*, 49. https://doi.org/10.3390/virtualworlds4040049

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Projection mapping (PM), also called spatial augmented reality, aims to seamlessly merge physical and virtual worlds by superimposing computer-generated graphics onto real surfaces [1–5]. Projection mapping has emerged as a transformative tool in museum exhibitions, allowing dynamic, immersive experiences that enhance visitor engagement with cultural heritage artifacts [6–8]. Museums utilize projection mapping to create interactive environments in which visitors can explore historical elements through augmented visuals, sound, and motion, thus fostering deeper educational and emotional connections. As a result, projection mapping is increasingly recognized as an essential tool for museums aiming (i) to modernize their exhibitions while preserving historical authenticity, (ii) to raise awareness on significant societal issues, and (iii) to engage community stakeholders, thus strengthening museums' role as community hubs and society's stewards of culture and education [5–8].

This work presents an advanced tabletop projection mapping system for museum exhibitions, called the Gaia System, describing its backend and frontend implementation and its user evaluation. The Gaia System is installed at the Sortland Museum in the Vesterålen

district, Norway, and by accommodating both brief and extended interactions, the system aims to raise awareness on topics related to the local society, economy, and environment, inspire action, and support the development of more sustainable behavior patterns within the community. With its striking aesthetic qualities—amplified by the visually engaging augmented reality features of projection mapping—the installation serves as a compelling exhibit in its own right. At the same time, it elevates the museum's role from a traditional exhibitor and curator of culture to an active participant in communicating and contributing to pressing global issues, such as climate change [5,6].

This research addresses the question "How can museums use PM technology to meaningfully engage visitors and stakeholders with societal issues?" and aims to present a PM platform while evaluating its usability and user experience in a real museum context. While existing PM installations in museums offer strong narrative and aesthetic value, they are generally designed as fixed experiences with limited capacity for ongoing data integration or curatorial modification. This study contributes a different model: the Gaia System, a PM platform designed for sustained institutional use through (i) scientific visualization of geographical data, (ii) interactive, multi-user PM functionality, including role-based access (e.g., guide vs. visitor) and content splitting, (iii) a customized user interface for managing PM content and providing topical information, (iv) the integration of both real-time and local data streams, and (v) structured data onboarding mechanisms tailored to small and medium-sized enterprises (SMEs). By reframing projection mapping as operational infrastructure rather than a fixed display, this work offers practical guidance for researchers advancing PM methodologies and museum practitioners deploying innovative, technology-driven exhibitions.

The paper is structured as follows: Section 2 reviews prior work on projection mapping in museums and identifies open challenges. Section 3 presents the Gaia System, describing its concept, target users, hardware and software setup, interaction modes, content model, and supporting tools. Section 4 reports the field study design, instruments, and results. Section 5 discusses the findings, design implications, and limitations, while Section 6 concludes and outlines future work.

2. Related Work

The adoption of projection mapping in museums and cultural heritage sites has evolved significantly over the past decade, driven by the need for engaging, non-intrusive, and technologically enhanced forms of cultural mediation.

A key trajectory in state-of-the-art PM applications in museums and cultural heritage contexts is the integration of interactive storytelling. Nikolakopoulou et al. [6] examined how PM can support the narration of intangible cultural heritage by overlaying visuals onto a physical model, enabling layered storytelling without altering the artifact. This aligns with the trend toward non-destructive augmentation, a critical requirement in cultural heritage contexts. Yuan and Alizadeh [8] examined how PM in cultural tourism can be enhanced through Ryan's interactive narrative framework, demonstrating how different modes of interaction—internal, external, exploratory, and ontological—can deepen visitor engagement, improve narrative coherence, and increase the educational and cultural value of heritage site experiences.

Another important dimension of the current state-of-the-art is the use of multisensory environments that combine PM with sound, motion, or tactile feedback to enhance immersion. Li and Ito [7] found that PM-based exhibits outperformed traditional static displays in both engagement and educational outcomes, reinforcing projection mapping as a proven interpretive medium in museum settings. This reflects a broader shift from passive

visualization toward exploratory and embodied interaction, supporting more meaningful visitor engagement.

From a technological standpoint, systems for geometric calibration, photometric compensation, and dynamic projection mapping have sought to improve the precision, adaptability, and user-friendliness of projection-mapping installations [1]. Grundhöfer and Iwai's foundational work [1] addressed calibration and alignment challenges, which remain relevant today, especially in environments with complex surfaces or lighting conditions. More recent advances integrate real-time tracking and adaptive rendering, enabling projection mapping to respond to visitor movement or role-specific inputs.

Despite these advancements, significant gaps remain. Most PM systems in museums are curator-driven and lack end user configurability. They also typically operate as closed loops, without the ability to ingest real-time or scientific data, which limits their potential for communicating contemporary or evolving societal issues such as climate change. Additionally, multi-user interaction and role-based content delivery are rarely explored, leaving out collaborative or differentiated user experiences (e.g., guides vs. visitors).

The Gaia System addresses these gaps and extends the state-of-the-art in PM for museums, offering a scalable, customizable, and socially engaged model for digital curation. It does so through the integration of dynamic geographical visualizations, content management interfaces, real-time and historical data streams, and structured onboarding for SMEs.

3. The Gaia System

3.1. Concept

The Gaia System's overall purpose is to inform users about the history of the area and to demonstrate how the environment has changed over the years and how it may change in the future. By visualizing sets of socio-economic, environmental, and historical data on the physical scale model, the system creates a digital twin of the region and enables users to interact with it and explore the available data (Figure 1).

For the design of the Gaia System, a set of high-level requirements (R) was established to guide the development process. These requirements were formulated through close collaboration with project partners, drawing upon their domain expertise and practical experience in museum settings, where visitor engagement and operational maintainability are critical. They also reflect the needs of potential end users, such as small and medium-sized enterprises (SMEs), which typically operate under limited technical resources. In addition, the requirements were informed by the relevant literature, as described above (Section 2). Together, they address the system's scope, maintainability, interactivity, content, usability, and experiential qualities and are presented as follows:

(R1) The system's physical scale model should cover the Vesterålen area and its islands.
(R2) The system should be maintainable by a small technical team, such as those typically found in small and medium-sized enterprises (SMEs).
(R3) The system should support both multi-user interaction (i.e., interaction with as many museum visitors as possible simultaneously) and a tour guide functionality.
(R4) The system content should cover topics related to society, economy, and environment, including infrastructure, roads, urban settlements, population density, waste management, climate change, agriculture, and fisheries.
(R5) The system content should cover the history of the place, the current situation, and forecasts for the future.
(R6) The system should enable the exploration of content from multiple perspectives, including obtaining an overall overview, focusing on specific places or events, and examining subjects across temporal dimensions.

(R7) The system should facilitate the combination of scientific/data-driven and popular-science/story-driven visualizations.
(R8) The system data format shall be flexible, extensible, and widely compatible with existing applications and libraries, while supporting future scalability.
(R9) The system should be user-friendly and communicate information clearly and concisely.
(R10) The system should be aesthetically pleasing and involve a "wow" factor so that it provides initial engagement for users and then moves on from there.

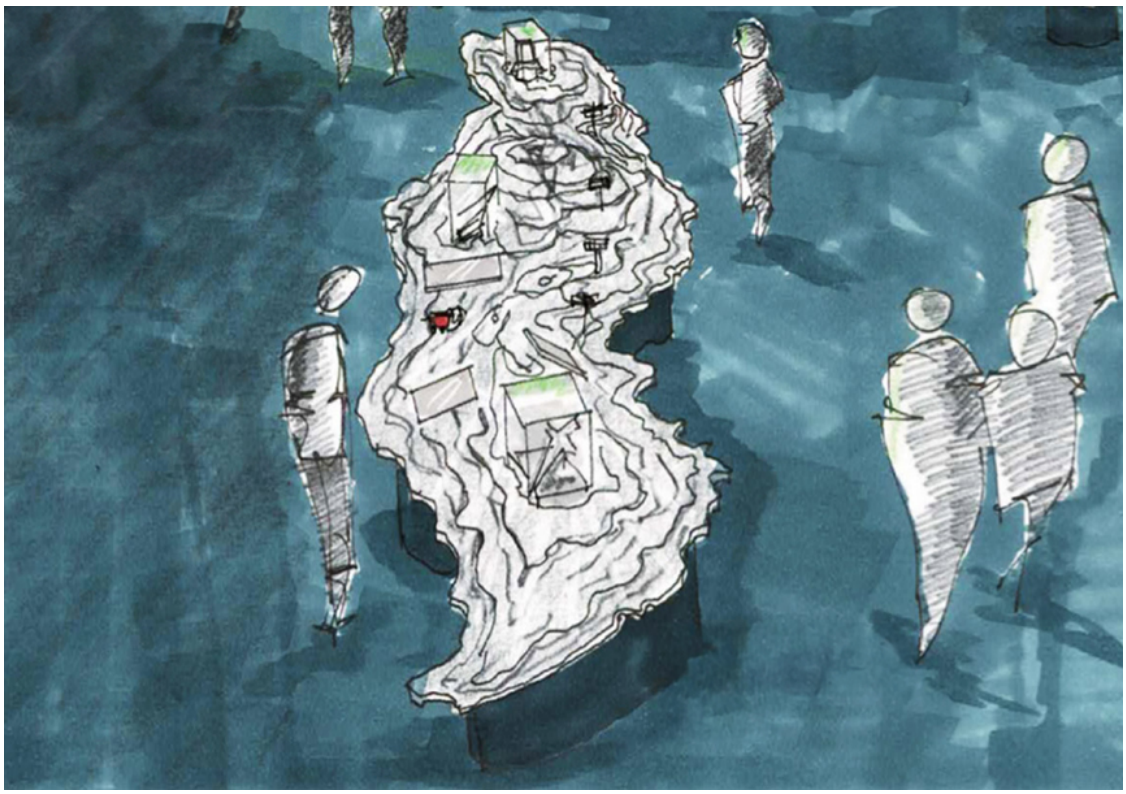


Figure 1. Conceptual sketch of the Gaia System installation, positioned in the museum room.

Based on requirements R1–R8, together with the informal feedback gathered from previous demonstrations of the system, an iterative design process was carried out, leading to the development of the second prototype of the Gaia System. Requirements R9–R10, which concern usability and experiential aspects, will be addressed in the subsequent evaluation phase (Section 4). Earlier versions of prototype 1 (demonstration video of prototype 1.1: https://boletsis.net/gaia/prototype1/, accessed on 17 October 2025 and prototype 1.2: https://boletsis.net/gaia/pmsl/, accessed on 17 October 2025) [5,9] were presented previously, highlighting the system requirements, the early design process, and its real-time data visualization capabilities. The current work extends the previous work and presents its second high-fidelity prototype, operating at a Technology Readiness Level (TRL) of 7, i.e., "System prototype demonstration at an operational environment".

3.2. Target Users

The Gaia System is designed for museum visitors in the Vesterålen district, encompassing a diverse user base that includes tourists, such as those arriving via the Hurtigruten coastal cruises with limited time ashore, local residents, and community stakeholders like students and representatives of local organizations and businesses.

Museum staff are also a key target group, as they play a dual role: (i) being system users themselves who actively demonstrate specific system content to visitors and (ii) curating its content by creating and editing elements to ensure it remains relevant and engaging.

3.3. System Setup and Apparatus

The Gaia System is centered around a 2.7 × 5.2 m physical 3D model of the Vesterålen region (addressing R1, Section 3.1), serving as a physical interface for immersive data visualization (a video presentation is available at https://boletsis.net/gaia/prototype2/index.html#v1, accessed on 17 October 2025). Nine ceiling-mounted Optoma UHZ65LV projectors deliver high-resolution 4K projections onto the model, dynamically presenting environmental information and narratives. The projection system is managed using three desktop PCs and uses MadMapper (https://madmapper.com/) as the primary projection mapping software. The setup is managed by a technical team consisting of 4–5 people (thus addressing R2, Section 3.1).

In addition to the main installation, the system includes three 27-inch touchscreens, each powered by a dedicated mini PC, allowing visitors to interact with the content and explore specific themes in greater detail. Supplementary content is displayed on a large backwall using three standard projectors, also powered by the exhibition's desktop PCs, providing contextual or supporting visuals that enhance the overall experience (Figure 2).

To coordinate playback across the nine projectors, all rendering PCs use a shared time protocol inspired by the Simple Network Time Protocol (SNTP) and implemented over Message Queuing Telemetry Transport (MQTT). This allows videos and visual events to start at approximately the same time on each node, though the individual display outputs are not hardware-synchronized due to cost constraints. MadMapper operates with standard vertical synchronization (v-sync) to maintain consistent frame pacing at 60 Hz, providing a refresh interval of roughly 16 ms. Periodic calibration is performed to correct for projection drift on the physical model and maintain overall visual continuity.



Figure 2. A figure of the room with explanatory text over each element in white font.

3.4. Interaction

The Gaia System supports two distinct interaction modes, designed to accommodate both individual exploration and guided demonstrations (thus addressing R3, Section 3.1).

Visitor mode (Figure 3) allows visitors to explore the system independently through three dedicated touchscreens (referred to as *user controllers* in the interaction context). To facilitate simultaneous use by multiple visitors without overlap on the projected content, the map is divided into the five municipalities of Vesterålen, with each user controller linked to specific municipalities. More specifically, the correspondence between the user controllers and the municipalities of the Vesterålen region is as follows:

- Controller 1: Sortland (walkthrough video: https://boletsis.net/gaia/prototype2/index.html#v2, accessed on 17 October 2025) and Hadsel municipalities;
- Controller 2: Andøy municipality;
- Controller 3: Øksnes and Bø municipalities.

This configuration ensures that visitors can interact with the system in parallel without interfering with each other's projected content (i.e., each user has their own projected area). The current setup uses three controllers for five municipalities, which means that users of two controllers (nr. 1 and 3) must select the municipality they wish to interact with, before beginning. The design could be scaled to five controllers in the future, enabling a one-to-one correspondence between user controllers and municipalities.

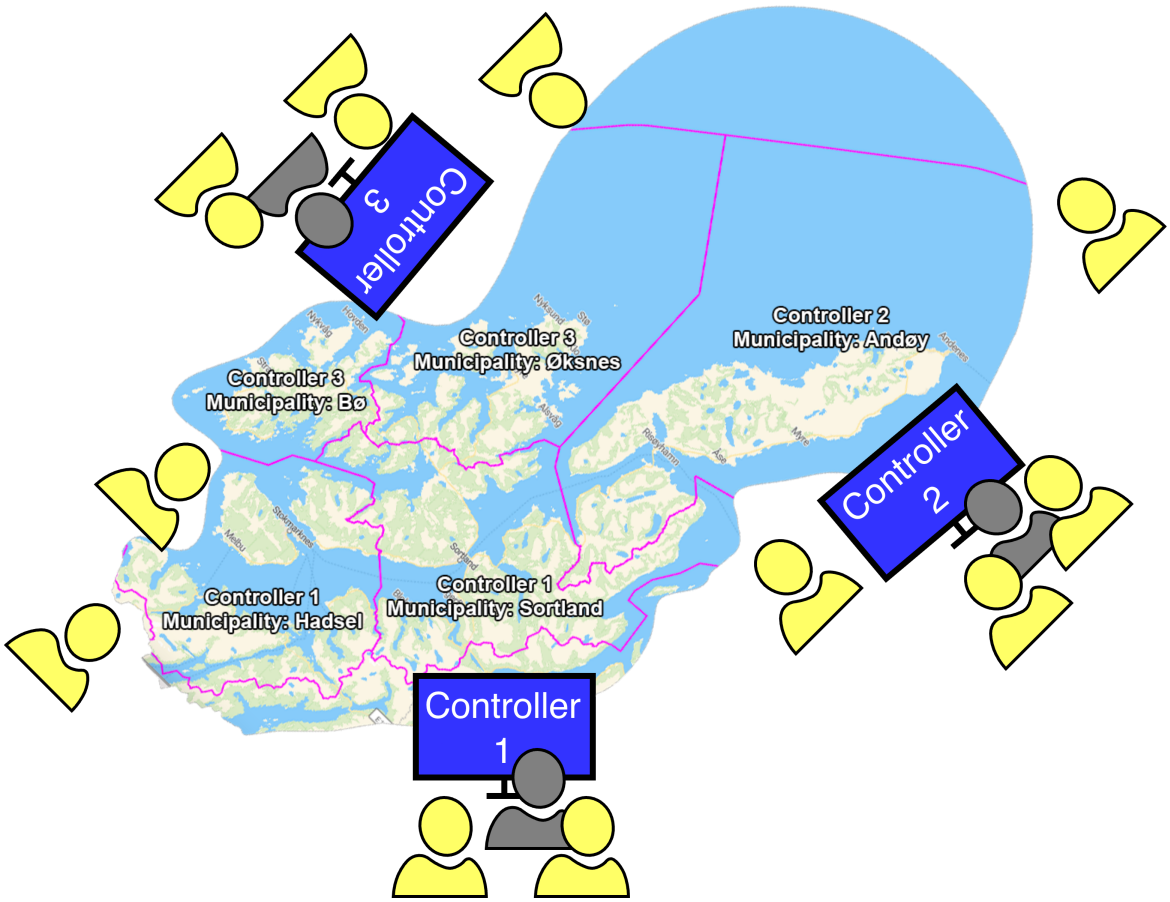


Figure 3. The Visitor interaction mode as a top-down schematic of the 3D model with museum visitors around it. Visitors using the touchscreens/controllers are shown in grey, while spectators are shown in yellow. The map displays the borders of the municipalities (purple lines) along with the corresponding controller assigned to each area.

Demonstration mode (Figure 4) is intended for group presentations led by museum staff. In this mode, the staff operates the system through a dedicated *admin controller*, i.e., a single tablet device, which provides access to all data across all municipalities. When Demonstration mode is active, the visitor touchscreens are disabled to prevent interruptions and ensure a smooth guided presentation.

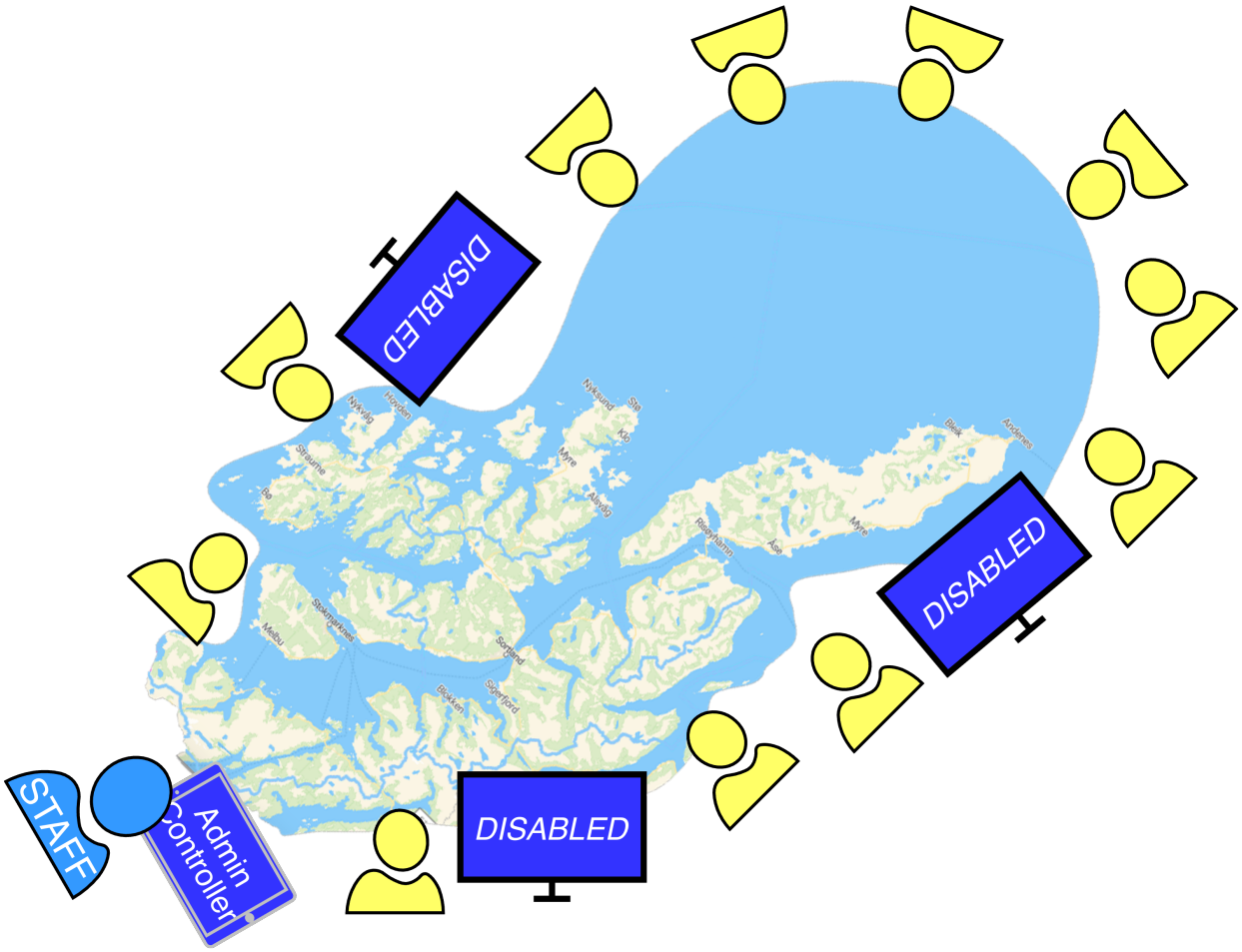


Figure 4. The Demonstration interaction mode as a top-down schematic of the 3D model with a museum staff member presenting to a group of visitors. The staff member holding the admin controller (tablet device) is shown in blue, while spectators are shown in yellow. All data are accessible through the admin controller.

3.5. System Content

In the Gaia System, content is visualized as thematic layers, triggered by the user and admin controllers (Section 3.4) and projected onto the 3D model through projection mapping. The content is provided in two main forms: *narratives* and *video animations* (thus addressing R7 of Section 3.1).

Narratives consist of interactive, map-based scientific visualizations that present historical, current (recent but not real-time), real-time, and forecasted data (addressing R5 of Section 3.1), obtained from formal and open authoritative sources. These narratives address a wide range of thematic areas, including human settlements, waste management, climate, wildlife, and related domains. To date, more than 40 narratives have been developed (addressing R4 of Section 3.1). The themes and narratives of the Gaia System, along with their data types and coverage, are presented in Table 1.

Table 1. The narratives of the Gaia System. A walkthrough of all narratives, as shown in the admin controller, is available at https://boletsis.net/gaia/prototype2/index.html#v3, accessed on 17 October 2025.

Themes	Narratives
Municipalities	Andøy [C], Bø [C], Hadsel [C], Sortland [C], Øksnes [C]
Infrastructure	Maritime [C], Road network [C], Lighthouses and lanterns [C], Coastal express [C], Roads [H], Airports [C]
Climate	Weather stations [HC], Climate challenges [CF]
Settlements	Population development [HC]
Waste	Farm mounds [H], Unregulated dump sites [H], Municipal landfills [HC], Reno-Vest recycling stations [C]
Wildlife	Moose [C], Greylag goose [C], Grey gull [C], Cod [C], Orca [C]
Agriculture	Cultivable land [C], Peatland [C], Animal types [C], Sheep per sq.km [C], Released sheep-lambs [C], Lost sheep-lambs [C], Overgrowth [C]
The Sea	Fishing vessels [HR], Cargo ships [HR], Passenger ships [HR], All vessels [HR], Fishing facilities [R], Fish farming [C], Boat discoveries [C]
GaiaDrøv	Sheep in real time [R]

Data types per narrative: *H* = Historical data, *C* = Current data, *R* = Real-time data, *F* = Forecast data.

The video animations are story-driven popular-science animations that visualize specific historical topics and events. In this prototype, two video animations were produced (Table 2).

The Gaia System content is available in two languages: Norwegian and English.

Table 2. The video animations of the Gaia System.

Title	Description	Duration
Tussa and the Trolls	Animation based on a local fairytale explaining how certain landscape features in the area came to be. Displayed on all three screens surrounding the model and on the model surface.	3 min 3 s
The Shelf Edge (Eggakanten)	Playful animated background for the sea-depth layer, showing sea creatures, submarines, and a shipwreck in a continuous loop projected behind the live layers.	3 min (loop)

3.6. Content Visualization

Each narrative in the Gaia System is visualized in two locations (Figure 5): on the controller (touchscreen or tablet), where it is triggered and accompanied by explanatory information, and on the 3D model, where additional information is presented through projection mapping.

On the controllers, users are presented with text-based and image-based information for the narratives they trigger. The content visualization and interaction begin with the Municipalities theme, immediately highlighting the area or municipality under the user's control. The controller interface, developed using the React library (https://react.dev/), is implemented in three types, depending on how the information is intended to be communicated (addressing R6 in Section 3.1):

- *Basic*: This interface type provides an overall perspective on a topic. It includes an approximately 100-word descriptive text and three related photographs (Figure 6a).
- *Highlight*: This interface type provides more detailed information about specific places on the map. It includes an approximately 100-word descriptive text for the overall topic, while selected places are supplemented with additional text-based descriptions and one to three related photographs (Figure 6b). On the 3D model, a "spotlight" visualization metaphor is employed (Figure 6c), highlighting the selected place to help users locate it easily.

- *Slider*: This interface type provides a temporal overview of a specific topic. It includes an approximately 100-word descriptive text and a slider for triggering the corresponding information. Each slider tag (i.e., time period) may be supplemented with additional descriptive text and graphics (Figure 6d).



Figure 5. A user controller (touchscreen) and the 3D model of the Gaia System.

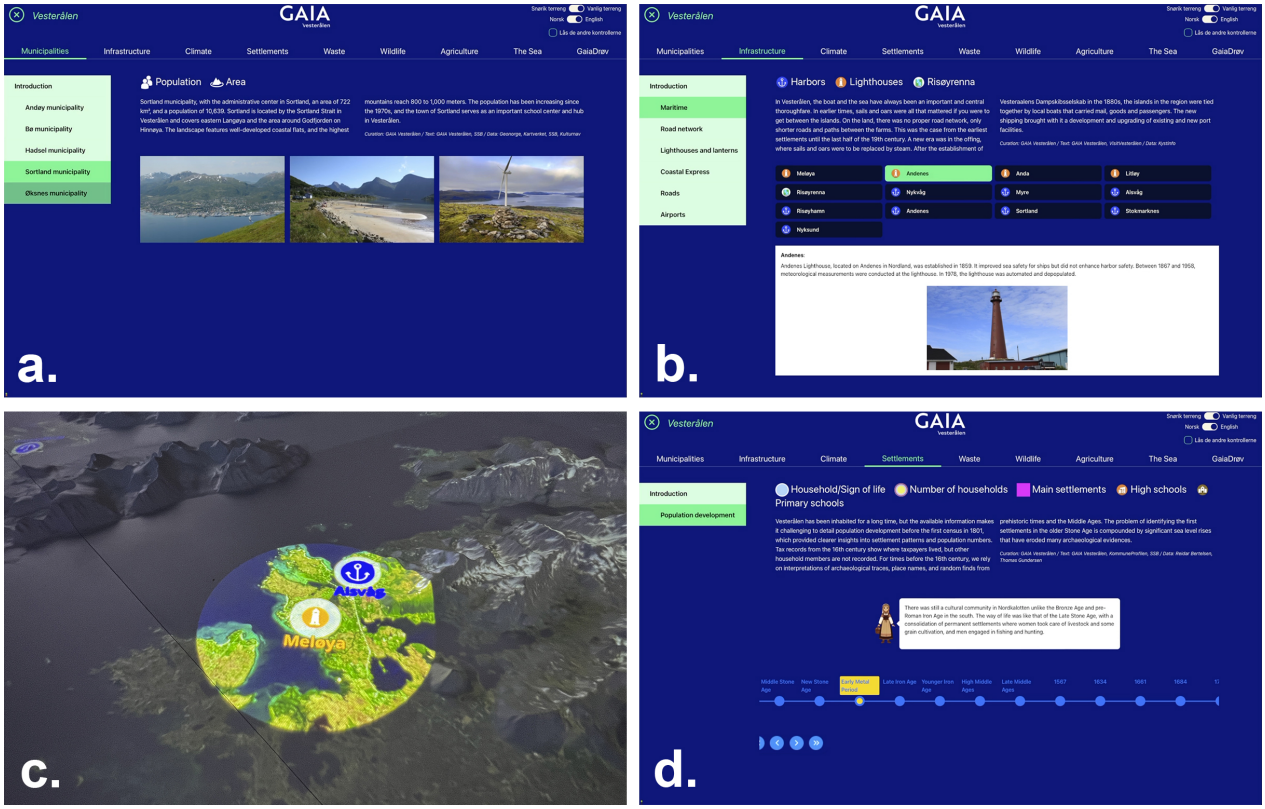


Figure 6. The various interface types of the controller: (**a**) the Basic interface type; (**b**) the Highlight interface type and (**c**) its "spotlight" visualization metaphor; and (**d**) the Slider interface type.

In all interface types, there is clear attibution of the data sources. In Demonstration mode, the content of the admin controller is mirrored onto the backwall projection, allowing the entire visitor group to follow the presentation. All controllers display map legends corresponding to the content projected onto the 3D model. This starts with the Municipalities theme for users to see the area that they are managing.

On the 3D model, narratives are visualized primarily through cartographic objects such as points, lines, and polygons, created using the Mapbox GL JS (https://mapbox.com/mapbox-gl-js/, accessed on 17 October 2025) and Deck.gl (https://deck.gl/) libraries, with text added when necessary to display place names. In addition, overlaid graphics/icons and numerical figures are occasionally used and are explained in the map legends, provided on the controllers (Figure 7). This design choice ensures that the content projected onto the 3D model remains language-agnostic for technical reasons, while all translations are handled at the user interface (controller) level.

Finally, the video animations, described in Table 2, are visualized exclusively on the 3D model and the backwall projections. They are activated via buttons on the admin controller, and no additional information is displayed on the controller while they are playing.



Figure 7. Graphics, images, and numerical figures showing the effects of forecasted 200-year storm surge for 2090 on the 3D model.

3.7. Content Development

3.7.1. Local Data

All local datasets (historical, current, and forecast data) used in the Gaia System were obtained from open-data sources, such as GeoNorge (https://geonorge.no), The Norwegian Mapping Authority (https://kartverket.no), The Norwegian Meteorological Institute (https://met.no), Statistics Norway (https://ssb.no), OpenStreetMap (https://openstreetmap.org), KulturNav (https://kulturnav.org), Artsdatabanken (https://artsdatabanken.no), The Directorate for Cultural Heritage (https://riksantikvaren.no), Wikipedia (https://wikipedia.org), and Ut.no (https://ut.no) and transformed into the JSON format, where necessary. The JSON format was selected as the backbone of the system, addressing R8 (Section 3.1), due to its simplicity, wide compatibility with most applications and libraries,

and its flexibility for future development, for instance, in the case of potential migration to a content management system (CMS). When richly annotated, JSON-based structures can also serve as the foundation of a lightweight knowledge management system, enabling the organization, retrieval, and reuse of information across different contexts [10,11].

Each narrative consists of two JSON-based files:

- A JSON file containing the information to be displayed on the controllers. A short JSON snippet for a narrative (Basic interface type) is presented below, while a JSON example for the "Airports" narrative is provided in Appendix A.1. The snippet contains the legend information, a 100-word descriptive text, data source attribution, and three photographs with captions, essentially giving an interface output, like Figure 6a. All text is provided in both Norwegian and English.

```
{
  ‘‘type’’: ‘‘Feature’’,
  ‘‘properties’’: {
    ‘‘narrative_no’’: ‘‘...’’,
    ‘‘narrative_en’’: ‘‘...’’,
    ‘‘description’’: { ‘‘no’’: ‘‘...’’, ‘‘en’’: ‘‘...’’ },
    ‘‘media’’: [
      { ‘‘image’’: ‘‘...’’, ‘‘caption’’: ‘‘...’’, ‘‘source’’: ‘‘...’’ }
    ],
    ‘‘legend’’: { ‘‘no’’: ‘‘...’’, ‘‘en’’: ‘‘...’’ }
  }
}
```

- A GeoJSON file containing the geographic features to be visualized on the 3D model. A short GeoJSON snippet is presented below. A GeoJSON example for the "Airports" narrative, including all language variants and media fields, is provided in Appendix A.2. The snippet contains one geographical point, along with its title, which is displayed on the 3D model. This is visualized on the map as a colored dot at these coordinates, with the title written next to it.

```
{
  ‘‘type’’: ‘‘Feature’’,
  ‘‘properties’’: {
    ‘‘narrative_no’’: ‘‘...’’,
    ‘‘narrative_en’’: ‘‘...’’,
    ‘‘municipality’’: ‘‘...’’,
    ‘‘title_map’’: ‘‘...’’
  },
  ‘‘geometry’’: {
    ‘‘type’’: ‘‘Point’’,
    ‘‘coordinates’’: [ ..., ... ]
  }
}
```

In the case of specialized interface types, such as Highlight and Slider (Section 3.6), additional GeoJSON properties are employed to provide descriptive text, related photographs, and corresponding slider tags, resulting in interface outputs such as those shown in Figure 6b,d.

The styling of the 3D model and map elements is defined globally; however, feature-level GeoJSON properties (e.g., point, line, or polygon color; text color and offset; point radius; and line width) can override these defaults to allow customized styling and visualization of individual elements on the 3D model when required (e.g., to resolve overlapping features).

For Visitor mode (Section 3.4), the data are divided according to the five municipalities of Vesterålen, with each feature assigned a corresponding "municipality" property in the GeoJSON file. To achieve this, Python 3 scripts together with the Shapely library (https://shapely.readthedocs.io/, accessed on 17 October 2025) were used to annotate the GeoJSON features with a "municipality" property, derived from polygon-based municipality boundaries.

To ensure the integrity and maintainability of the JSON/GeoJSON datasets, all narrative files are managed in a Git-based version control repository. Although no personal or sensitive data is stored, basic security practices are applied: repository access is restricted to project maintainers, regular backups are retained, and schema validation checks are enforced to prevent file corruption or malformed data from entering the system.

3.7.2. Real-Time Data

For real-time data, the system is connected to external APIs, such as the BarentsWatch API (https://barentswatch.no/) for The Sea theme and the live GPS positions of sheep for the GaiaDrøv theme (Table 1), on an ad hoc basis, with custom integration modules developed and adapted to fit the Gaia System's data architecture and runtime requirements.

3.7.3. Video Animations

The PM video animations (Table 2) were produced as HAP Alpha-encoded QuickTime (.mov) files, optimized for real-time playback within the MadMapper software. These animations were created by the media production company Deadline Media (https://deadline.no/), in collaboration with museum experts.

3.8. System Architecture

The system architecture, as illustrated in Figure 8, is organized as a workflow beginning with the two main categories of incoming data sources: local data and API data. Local data is stored within the application and directly assessed. These can be divided into two categories based on their use and structure (as also mentioned in Section 3.7.1). The first is controller UI data, stored in JSON format, which provides the content for the touchscreen user interfaces. The second is map data, stored in GeoJSON format, which ensures compatibility with the base map library Mapbox (https://mapbox.com/). Mapbox enables customizable interactive maps and geospatial visualization for web and mobile applications.

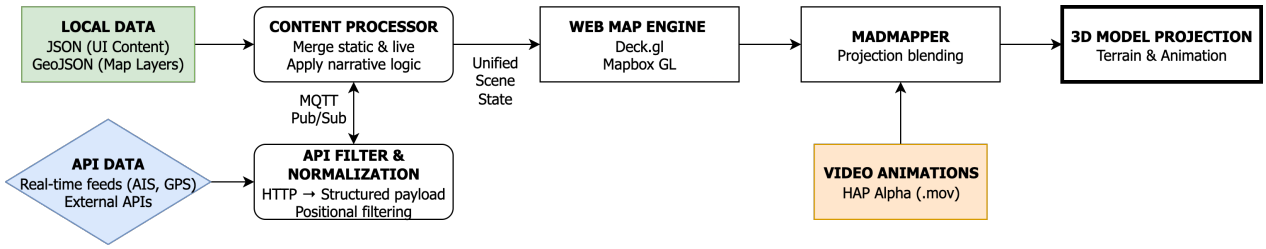


Figure 8. The architecture of the Gaia System.

In addition to local data, the system ingests external data through APIs, depending on the selected narrative and theme. For the Gaia System, this includes live vessel tracking data from BarentsWatch and live GPS positions of sheep for GaiaDrøv. The API data is subsequently filtered and normalized into GeoJSON format based on geographic position (longitude and latitude), either encompassing the entire Vesterålen region or restricted to a specific municipality. The resulting feed is then transmitted to the application via MQTT, ensuring low-latency delivery for visualization [9]. Before rendering, these streams are passed through a content processor, where static GeoJSON layers and live API feeds are

merged and narrative rules are applied to form a unified scene state. Once prepared, all data is rendered on the web interface, which integrates two complementary visualization frameworks designed for use with Mapbox maps, Deck.gl and Mapbox GL JS, for high-performance and interactive map-based overlays.

The final stage of the workflow is the projection mapping pipeline, which is implemented using the projection mapping software MadMapper. At this stage, the web interface, along with video animations, is imported into the software and projected onto the physical 3D model, thereby finalizing the workflow. The process is supported by a dedicated hardware setup, as described in Section 3.3. This architecture enables the system to integrate local and external data sources into a coherent digital visualization, generating high-resolution, spatially accurate projections on the physical 3D model.

3.9. Explorative Work

Explorative work around the Gaia System has also been carried out to investigate future directions and extensions. A series of tools and prototypes was implemented as small-scale feasibility projects to test ideas and inform future development. These ideas originated from museum staff, drawing on their expertise and experience with visitor needs.

- *Content management system:* A bespoke CMS, the PM Editor, was designed and implemented exclusively for the Gaia System to support narrative creation (Figure 9a,b). Its functionality is underpinned by the system's robust JSON-based content backend, which ensures structured and consistent handling of content. The PM Editor enables non-technical users to author narratives (of the Basic interface type) through a structured page form. It can serve as a "playground" for museum employees to experiment with new narratives, and it may also be used by special interest groups (e.g., students) to contribute their own content to the Gaia System.
- *Object tracking:* Object tracking was explored as a means to enable gaming and gamified experiences (Figure 9c). For example, a toy boat placed on the 3D model could be detected and used to trigger a narrative, illustrating how physical objects might be incorporated into interactive storytelling concepts, also using the physical qualities of the 3D model.
- *Natural user interfaces:* Experiments were also conducted with electric paint connected to an Arduino-based Bare Conductive board (https://www.bareconductive.com/, accessed on 17 October 2025). In this setup, painted conductive surfaces on or around the 3D model (Figure 9d) could be touched to playfully trigger narratives, creating a tangible and gamified interaction experience that extended the possibilities of narrative activation.
- *Marker-based augmented reality:* The integration of augmented reality (AR) content on top of the Gaia System was explored as a way to extend the experience beyond projection mapping (Figure 9e). For example, AR could be used to visualize air traffic and CO_2 emissions by utilizing the vertical dimension, which projection mapping alone cannot represent. In addition, AR offers an alternative activity for visitors who are observing rather than directly interacting with the touchscreens, thereby enhancing engagement for a broader audience.

It should be noted that the explorative work described above was not included in the formal evaluation of the Gaia System prototype. These concepts were developed as feasibility studies to test future possibilities, and their further development will depend on alignment with user needs and feedback gathered through ongoing and future evaluations. At the same time, the explorative work is presented here to provide practitioners and researchers in the field with grounded suggestions and ideas, informed by the expertise of museum professionals.

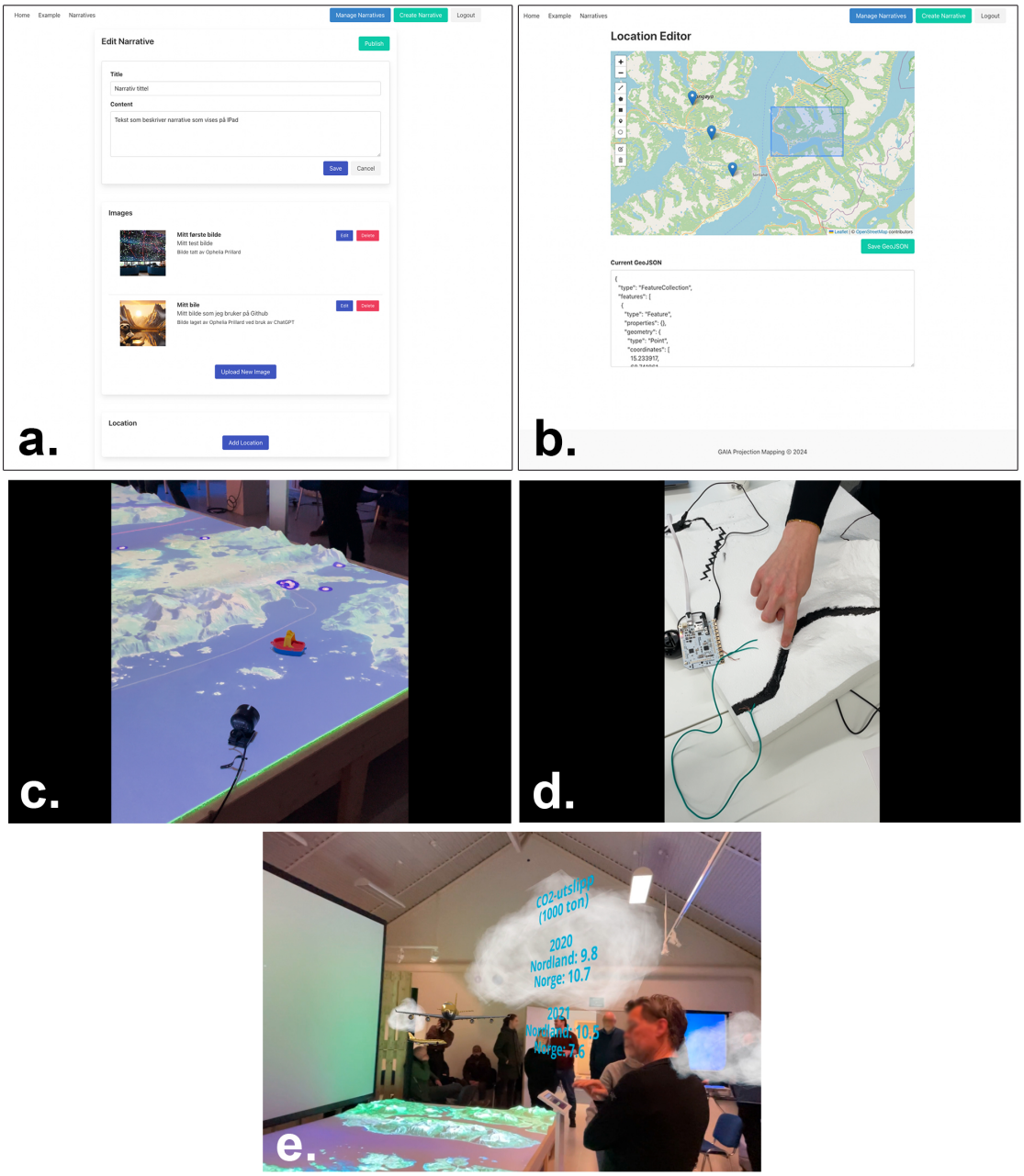


Figure 9. The explorative work conducted around the Gaia System: (**a**,**b**) a bespoke content management system for narrative creation; (**c**) object tracking for gamified experiences; (**d**) painted conductive surfaces on the 3D model for gamified interactions; and (**e**) marker-based augmented reality extending the physical 3D model.

4. Evaluation

A field study was conducted to evaluate the Gaia System prototype, employing an online survey to collect participant feedback. The study took place during the first week of June at the Sortland Museum in Sortland, Norway, in the context of the Gaia Arctic Summit (https://gaiaarcticsummit.eco/) and the EU-funded RESIST project's consortium meeting (https://resist-project.eu/), both organized by Museum Nord. During this period, visitor groups of 25–35 participants were invited to experience the Gaia System in sessions. The groups comprised stakeholders, researchers, business representatives, environmental experts, engaged citizens, and municipal employees from Norway and across Europe.

Each session was standardized across all groups. It began with the system presented in Demonstration mode, during which museum staff demonstrated the content of the

narratives and concluded with the video animations (total duration: approximately 20 min). Then, the Visitor mode followed, where participants explored the system independently using the touchscreens (approximately 25 min). After the interaction, participants were provided with a QR code/web link to the online survey.

The evaluation survey was conducted anonymously and was developed using the open-source LimeSurvey CE platform (https://community.limesurvey.org/). It was designed to be completed quickly—within approximately 10 min—in order to accommodate opportunistic participation in a museum setting, while still capturing all necessary information for the evaluation. It consisted of the following parts:

- First, *informed consent* was obtained from all participants.
- Then, *demographic questions* about age, gender, and previous projection mapping experience were asked.
- To measure perceived usability, the 10-item *System Usability Scale (SUS)* questionnaire [12] was used. The SUS is an instrument that allows usability practitioners and researchers to measure the subjective usability of products and services. Specifically, it is a 10-item questionnaire that can be administered quickly and easily and returns scores ranging from 0 to 100. SUS scores can also be translated into adjective ratings, such as "worst imaginable", "poor", "OK", "good", "excellent", and "best imaginable", as well as into grade scales ranging from A to F. The SUS has been shown to be a reliable and valid instrument, robust with a small number of participants, and to have the distinct advantage of being technology-agnostic, which means it can be used to evaluate a wide range of hardware and software systems [12–14].
- Then, the short version of the *User Experience Questionnaire (UEQ-S)* was administered [15–17]. The UEQ-S consists of eight items expressed as bipolar adjective pairs. Four items measure Pragmatic Quality (e.g., "obstructive–supportive", "complicated–easy"), while four items measure Hedonic Quality (e.g., "boring–exciting", "conventional–inventive"). Responses are scored on a 7-point scale from −3 (extremely negative) to +3 (extremely positive). The UEQ-S also allows for benchmarking against established datasets of user experience evaluations across a wide range of products and systems. Compared to the full UEQ, the short version maintains good internal consistency and has been shown to be suitable for rapid feedback collection in constrained environments. Its main advantage is brevity, requiring less than two minutes to complete. This efficiency, however, comes at the cost of reduced granularity, as it does not cover all six dimensions of the original questionnaire (e.g., attractiveness, dependability). Despite this limitation, the UEQ-S remains a robust tool for capturing the core dimensions of user experience in time-sensitive contexts such as museum visits [15–17].
- Finally, participants were asked two open-ended questions regarding *what they liked* and *what they did not like* about the Gaia System. These questions were included to allow participants who wished to elaborate further on their usability and user experience impressions to provide more detailed feedback and to help the researchers pinpoint specific problematic areas. The responses were analyzed using open and axial coding, where the core concepts and themes were identified.

Informal pilot testing confirmed that the survey could be completed within 7–10 min, which was essential in a museum setting where visitors could not be interrupted or constrained by structured tasks. For the same reason, instruments such as the SUS and UEQ-S were chosen: they provide validated insight into usability and user experience without requiring controlled interaction or performance measurement. In a free-exploration context, task-based evaluation would have imposed artificial constraints inconsistent with the

natural use of the system. Together with open-ended feedback, these two scales can offer sufficient depth while respecting the conditions of live public deployment.

Results

A total of 32 participants completed the evaluation survey ($N = 32$; mean age: 37.69; SD: 7.45; male/female: 15/17). Regarding prior experience with projection mapping technologies, 29 participants reported no prior experience, 2 participants indicated having encountered it once before, and 1 participant had experienced it a few times.

Table 3 presents a summary of the usability and user experience scores for the Gaia System.

Table 3. Usability and user experience scores for the Gaia System ($N = 32$).

Metric	Mean	SD
SUS	84.14	6.24
UEQ-S Overall	1.93	0.35
UEQ-S Pragmatic Quality	1.89	0.38
UEQ-S Hedonic Quality	1.96	0.60

- The SUS yielded a mean score of 84.14 (SD = 6.24), which corresponds to a SUS grade of B, based on the grading scale from [13]. According to the adjective rating scale, this score is positioned close to the "Excellent" category, indicating a high level of usability.
- The UEQ-S further provided insights into user perceptions (Figure 10). The results showed high values across both dimensions, with Pragmatic Quality achieving a mean of 1.89 (SD = 0.38) and Hedonic Quality achieving a mean of 1.96 (SD = 0.60). Therefore, the Overall score was also high, with a mean of 1.93 (SD = 0.35).

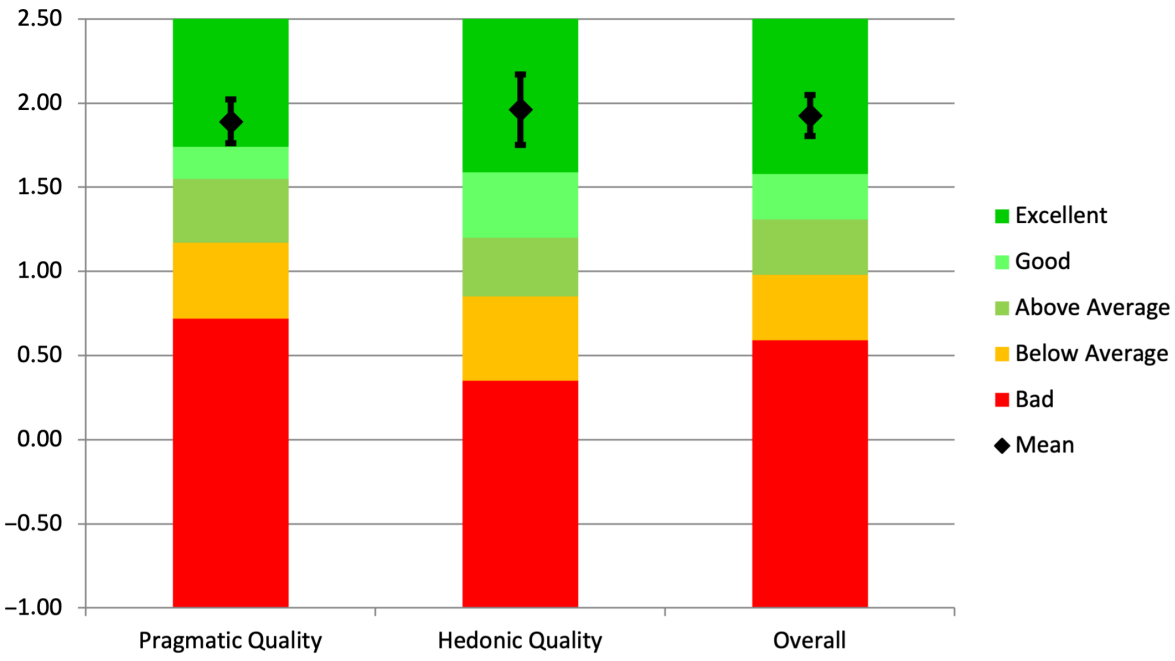


Figure 10. Mean UEQ-S scores (with standard deviation bars) for the Gaia System.

Finally, the remarks collected through the two open-ended questions are presented in Table 4, ordered by frequency from the most frequent to the least frequent remark.

Table 4. Participant feedback on the Gaia System, presented in order of frequency from most to least mentioned remarks.

Positive remarks
+ The projection mapping was impressive, with high-quality colors, resolution, and map visualization. + It was easy to independently interact, use the touchscreens and access the available information. + The projection mapping video animations were impressive and informative. + I learned about the region's history and current issues. + The real-time data delivered an instant sense of the real world.
Negative remarks
− There was too much information, and I needed more time to explore all narratives. − Layers of information sometimes overlapped when switching quickly (bug). − It was challenging, sometimes, to understand which information referred to the past, the present, and the future.

5. Discussion

5.1. Findings

Overall, the Gaia System achieved high usability and user experience scores, indicating that visitors were able to engage with the content effectively (addressing R9–R10 of Section 3.1). Participants' qualitative remarks—such as calling the system "impressive" and "easy to interact with"—aligned with the high SUS and UEQ-S scores, reinforcing the consistency between measured usability and perceived experience.

One of the most striking outcomes was the strong positive reception of the projection mapping technology itself. Participants consistently described the visual quality as impressive, underlining projection mapping's potential to deliver impactful and memorable museum experiences.

At the same time, the system's content was perceived as both informative and abundant. In particular, the video animations and the real-time data stood out, potentially offering a rich, structured storytelling experience and an engaging overview of reality, respectively. The JSON-based dataset structure enabled the integration of large volumes of data-driven content and the development of different interface types, shaped by the narratives museum experts sought to convey (Figure 6). While the ease of content integration supported the richness of information, some participants reported that the sheer amount of information felt overwhelming. In particular, the lack of a clear temporal structure—distinguishing past, present, and future information—emerged as a limitation, underscoring the importance of temporal annotation in data-driven narratives.

The touchscreen controllers gave users a sense of agency, and their interaction with them was considered straightforward and accessible, confirming the value of adopting familiar, widely understood interaction metaphors in public installations. Nevertheless, some technical limitations on the projection side became evident, including data pipeline bugs that caused overlapping visual layers on the 3D model when switching rapidly between narratives. Such issues highlight the need for robust technical optimization in systems with complex architectures that must integrate historical, current, real-time, and forecast data.

5.2. Implications

From these findings, several considerations may be useful for researchers and developers in the field of PM installations in museum settings, further supported by related work in the field and adjacent domains.

- *Designing PM installations to support multi-user experiences, accommodating both group engagement and simultaneous individual interactions, is promising.* In the case of the Gaia System, visitors can observe museum staff presenting the PM content (Demonstration mode) or actively engage with the content independently (Visitor mode). At the same time, the content splitting enables multiple users to interact simultaneously, creating a co-located experience. Allowing visitors to choose between passive observation and active participation, while also sharing the experience with other users, represents a promising strategy for fostering engagement with museum content [18,19].
- *Combining scientific, data-driven PM content with popular-scientific, story-oriented content is a compelling strategy.* The Gaia System combines historical, current, forecast, and real-time geographical data (Table 1) with video animations (Table 2). Data-driven narratives were considered highly informative across a wide range of topics, while the video animations focused on specific subjects and were aesthetically pleasing and engaging. This combination leverages the strengths of both approaches, potentially creating PM content that is both engaging and informative [20,21].
- *Clearly annotating, organizing, and carefully curating content to match the intended experience duration is significant for effective PM installations.* One of the major takeaways from the Gaia System study is the need for clear temporal annotation of the content, as well as careful curation to align with the PM installation's objectives and intended session duration. Naturally, content curation is an ongoing process, especially when current, real-time, and forecast data must be incorporated and regularly updated [22,23].
- *Positioning museum staff as a key target group—acknowledging their expertise and accommodating their technical skills—is a promising strategy for creating manageable PM installations.* In the Gaia System, museum staff were identified as a key target group because—apart from using the system themselves during Demonstration mode—they are also responsible for updating and curating its content. The backend, particularly the data-driven/local data component, was implemented to allow staff with limited technical expertise to edit the PM content. Moreover, further work on CMSs is underway to systematize this process even further. Consequently, treating museum staff as a key target group and facilitating their work may lead to improved visitor experiences [24,25].
- *Employing familiar visualization metaphors enables users to readily interpret PM content.* In the Gaia System, several popular map-based visualizations were used on the 3D model side. These metaphors align with everyday web use and widely known map applications, creating a user-friendly and familiar experience for visitors from the outset [26–28].
- *Intuitive interaction metaphors and popular and widely recognized interfaces ensure usability for diverse audiences.* In the Gaia System, users successfully interacted with a standard button-based web interface on the touchscreen controllers. This familiarity in the interaction design may influence users' sense of agency and acceptance of the system [29,30].
- *Adopting interoperable data standards is essential for ensuring scalability and portability across domains.* For the Gaia System's local data, the JSON standard was used with interoperability and scalability in mind. In this case, the chosen format is human-readable, which benefits museum staff who need to edit content, while also allowing files to be efficiently imported into a CMS. Interoperable data standards for PM installations can be a key factor in enabling system scalability and keeping content up to date [31,32].
- *Explorative development work underscores the importance of continuous experimentation, iteration, and updating to maintain relevance and impact in museum environments.* The current version of the Gaia System is the result of earlier exploratory work on enabling

simultaneous interaction by multiple users through touchscreen controllers, as well as on content splitting. Exploratory work grounded in museum staff expertise, ideation, and diverse technologies can drive innovation in museum settings [19,33].

5.3. Study Limitations

The methodological limitations of this study mirror those commonly reported in other projection mapping studies in museums and are typical in first deployments of new interactive installations (Section 2).

- *Single-site setting:* The evaluation was conducted at a single museum site, providing a controlled and well-documented context but limiting how far the findings can be generalized beyond the local visitor demographic and exhibition practices.
- *Convenience sampling:* Participants were recruited from visitors and invited stakeholders attending the Gaia Arctic Summit and the RESIST consortium meeting, offering a practically available audience that was diverse and familiar with the exhibition themes. While this group may have been somewhat more engaged and technology-oriented than the average museum visitor, it was well suited to an early, exploratory study of a new interactive installation. Detailed education and professional data were not collected, as the study focused on a realistic mixed audience typical of museum contexts rather than segmented user profiling.
- *Novelty effect:* Because the system was both visually striking and recently introduced, some of the high usability and enjoyment ratings may have been influenced by novelty—a common and expected effect when audiences encounter emerging technologies.
- *Self-report measures:* The evaluation relied on well-established self-report instruments (SUS, UEQ-S) and qualitative feedback rather than behavioral logging. This was appropriate for assessing perceived usability and user experience at an early deployment stage, while future studies could complement it with detailed interaction analytics and longitudinal follow-up.

Together, these choices reflect deliberate trade-offs to achieve a robust yet feasible first in situ assessment of the system.

6. Conclusions

In this work, the complete design process of the Gaia System was presented, together with the derived implications and design considerations, thereby supporting reproducibility and potentially informing the development of future PM installations in museums. The results position this Gaia System prototype as an effective demonstration of how projection mapping can be harnessed as an engaging, multi-user museum technology, while also identifying concrete areas for refinement—most notably in tailoring content curation to the intended visitor experience and ensuring technical stability.

Beyond implementation, the Gaia System reframes projection mapping as a communication infrastructure rather than a showcase medium. By enabling museum staff to author, update, and operate data-rich narratives with limited technical expertise, it introduces a new operational model for PM research, shifting the emphasis from temporary visual spectacle to long-term institutional use and ongoing content management.

Future iterations will address the documented issues, further enhancing the Gaia System's potential as both a research platform and a museum tool for science communication. Planned developments include the introduction of a new CMS built on the Sanity platform (https://sanity.io/), which will simplify content updates and will make the platform more accessible to museum staff, while providing APIs to enable future integrations. In addition, the narrative content will be curated and restructured to support shorter, approximately

20-min sessions, following a clearer temporal logic that moves from past to present to future across the different themes. Technical improvements will be made, and the focus will be on resolving the identified bugs in the data pipeline to ensure stable and reliable operation. Finally, part of the exploratory work on gamification, physical interaction, and AR, described in Section 3.9, will be further tested and evaluated with visitors in real-world use.

Author Contributions: Conceptualization: C.B.; methodology: C.B.; software: O.P. and C.B.; formal analysis: C.B. and O.P.; writing—original draft preparation: C.B.; writing—review and editing: C.B. and O.P.; visualization: C.B. All authors have read and agreed to the published version of the manuscript.

Funding: This work is funded by the Research Council of Norway under the Gaia Vesterålen project (no. 321550). The conceptualization, design, development, and evaluation of the Gaia System and its contents are funded by the Research Council of Norway under the Gaia Vesterålen project (no. 321550), except for the design and development of the Climate theme and its narratives (Table 1), which were funded by the European Commission through the RESIST project (Grant Agreement ID 101093968).

Institutional Review Board Statement: Ethical review and approval were waived for this study because the research was conducted entirely on fully anonymized data and did not involve the collection or processing of personal or sensitive information. In accordance with Norwegian regulations, such projects fall outside the scope of mandatory review by Sikt, the national data protection authority.

Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: The datasets presented in this article are not publicly available due to intellectual property restrictions, as they are owned by third parties (the project leader organization). Requests to access the datasets should be directed to the Gaia Vesterålen project leadership team: https://museumnord.no/vare-museer/sortland-museum/, accessed on 17 October 2025.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

3D	Three-dimensional
AR	Augmented reality
CMS	Content management system
GeoJSON	Geographic JavaScript Object Notation
JSON	JavaScript Object Notation
MQTT	Message Queuing Telemetry Transport
PC	Personal computer
PM	Projection mapping
R	Requirement
SME	Small and medium-sized enterprise
SNTP	Simple Network Time Protocol
SUS	System Usability Scale
UEQ	User Experience Questionnaire
V-sync	Vertical synchronization

Appendix A

Appendix A.1

An example mock-up of a JSON snippet for the "Airports" narrative (Basic interface type) is presented below.

```
{
‘‘type’’: ‘‘Feature’’,
‘‘properties’’: {
    ‘‘narrative_no’’: ‘‘Lufthavner’’,
    ‘‘narrative_en’’: ‘‘Airports’’,
    ‘‘source_data’’: ‘‘Lorem Ipsum’’,
    ‘‘legend_no’’: ‘‘<img src=’/airports.png’>Lufthavner<img src=’...’’,
    ‘‘legend_en’’: ‘‘<img src=’/airports.png’>Airports<img src=’...’’,
    ‘‘description_no’’: ‘‘I Vesterålen...’’,
    ‘‘description_en’’: ‘‘In Vesterålen...’’,
    ‘‘image1’’: ‘‘/narratives/lufthavner1.jpg’’,
    ‘‘image1_caption_no’’: ‘‘Caption Lorem Ipsum’’,
    ‘‘image1_caption_en’’: ‘‘Caption Lorem Ipsum’’,
    ‘‘image1_source’’: ‘‘Lorem Ipsum’’,
    ‘‘image2’’: ‘‘/narratives/lufthavner2.jpg’’,
    ‘‘image2_caption_no’’: ‘‘Caption Lorem Ipsum’’,
    ‘‘image2_caption_en’’: ‘‘Caption Lorem Ipsum’’,
    ‘‘image2_source’’: ‘‘Lorem Ipsum’’,
    ‘‘image3’’: ‘‘/narratives/lufthavner3.jpg’’,
    ‘‘image3_caption_no’’: ‘‘Caption Lorem Ipsum’’,
    ‘‘image3_caption_en’’: ‘‘Caption Lorem Ipsum’’,
    ‘‘image3_source’’: ‘‘Source Lorem Ipsum’’
    }
}
```

Appendix A.2

An example mock-up of a GeoJSON snippet for the narrative “Airports” is presented below.

```
{
‘‘type’’: ‘‘Feature’’,
‘‘properties’’: {
    ‘‘narrative_no’’: ‘‘Lufthavner’’,
    ‘‘narrative_en’’: ‘‘Airports’’,
    ‘‘municipality’’: ‘‘Hadsel’’,
    ‘‘title_map’’: ‘‘Stokmarknes (SKN)’’
    },
‘‘geometry’’: {
    ‘‘type’’: ‘‘Point’’,
    ‘‘coordinates’’: [
        15.024340355439733,
        68.5807389927052
        ]
    }
}
```

References

1. Grundhöfer, A.; Iwai, D. Recent advances in projection mapping algorithms, hardware and applications. In *Proceedings of the Computer Graphics Forum*; Wiley Online Library: Hoboken, NJ, USA, 2018; Volume 37, pp. 653–675. [CrossRef]
2. Nofal, E.; Stevens, R.; Coomans, T.; Moere, A.V. Communicating the spatiotemporal transformation of architectural heritage via an in-situ projection mapping installation. *Digit. Appl. Archaeol. Cult. Herit.* **2018**, *11*, e00083. [CrossRef]

3. Pezzullo, P.C. Between crisis and care: Projection mapping as creative climate advocacy. *J. Environ. Media* **2020**, *1*, 59–77. [CrossRef]
4. Yoo, H.; Kim, H. A study on the media arts using interactive projection mapping. *Contemp. Eng. Sci.* **2014**, *7*, 1181–1187. [CrossRef]
5. Boletsis, C. The Gaia System: A tabletop projection mapping system for raising environmental awareness in islands and coastal areas. In Proceedings of the PETRA '22, Corfu, Greece, 29 June–1 July 2022; ACM: New York, NY, USA, 2022; pp. 50–54. [CrossRef]
6. Nikolakopoulou, V.; Printezis, P.; Maniatis, V.; Kontizas, D.; Vosinakis, S.; Chatzigrigoriou, P.; Koutsabasis, P. Conveying intangible cultural heritage in museums with interactive storytelling and projection mapping: The case of the mastic villages. *Heritage* **2022**, *5*, 1024–1049. [CrossRef]
7. Li, H.; Ito, H. Comparative analysis of information tendency and application features for projection mapping technologies at cultural heritage sites. *Herit. Sci.* **2021**, *9*, 126. [CrossRef]
8. Yuan, Y.; Alizadeh, F. Optimizing Projection Mapping in Cultural Tourism through Ryan's Interactive Narrative Framework. *Malays. J. Soc. Sci. Humanit. (MJSSH)* **2024**, *9*, e003082. [CrossRef]
9. Boletsis, C.; Pultier, A.; Prillard, O. The projection mapping situational layer: Tabletop projection mapping for visualisation of real-time geospatial data. In Proceedings of the 16th International Conference on PErvasive Technologies Related to Assistive Environments, Corfu, Greece, 5–7 July 2023; pp. 245–246. [CrossRef]
10. Lanthaler, M.; Gütl, C. On Using JSON-LD to Create Evolvable RESTful Services. In Proceedings of the 3rd International Workshop on RESTful Design (WS-REST 2012), Lyon, France, 17 April 2012; ACM: New York, NY, USA, 2012; pp. 25–32. [CrossRef]
11. Siffa, I.C.; Schäfer, J.; Becker, M.M. Adamant: A JSON schema-based metadata editor for research data management workflows. *F1000Research* **2022**, *11*, 475. [CrossRef] [PubMed]
12. Brooke, J. SUS: A retrospective. *J. Usability Stud.* **2013**, *8*, 29–40.
13. Bangor, A.; Kortum, P.; Miller, J. Determining what individual SUS scores mean: Adding an adjective rating scale. *J. Usability Stud.* **2009**, *4*, 114–123.
14. Kortum, P.; Acemyan, C.Z. How low can you go? Is the System Usability Scale range restricted? *J. Usability Stud.* **2013**, *9*, 14–24.
15. Schrepp, M.; Hinderks, A.; Thomaschewski, J. Design and Evaluation of a Short Version of the User Experience Questionnaire (UEQ-S). *Int. J. Interact. Multimed. Artif. Intell.* **2017**, *4*, 103–108. [CrossRef]
16. Schrepp, M.; Sandkühler, H.; Thomaschewski, J. How to create short forms of UEQ+ based questionnaires? In Proceedings of the Mensch und Computer 2021-Workshopband, Ingolstadt, Germany, 5–8 September 2021. [CrossRef]
17. Hinderks, A.; Schrepp, M.; Thomaschewski, J. A benchmark for the short version of the user experience questionnaire. In Proceedings of the 14th International Conference on Web Information Systems and Technologies-APMDWE, Seville, Spain, 18–20 September 2018; SciTePress: Setúbal, Portugal, 2018; pp. 373–377. [CrossRef]
18. Falk, J.H.; Dierking, L.D. *The Museum Experience Revisited*; Routledge: London, UK, 2016.
19. Ciolfi, L.; McLoughlin, M. Designing for meaningful visitor engagement at a living history museum. In Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design, Copenhagen, Denmark, 14–17 October 2012; pp. 69–78. [CrossRef]
20. Lu, S.E.; Moyle, B.; Reid, S.; Yang, E.; Liu, B. Technology and museum visitor experiences: A four stage model of evolution. *Inf. Technol. Tour.* **2023**, *25*, 151–174. [CrossRef]
21. Pietroni, E. Multisensory Museums, Hybrid Realities, Narration, and Technological Innovation: A Discussion Around New Perspectives in Experience Design and Sense of Authenticity. *Heritage* **2025**, *8*, 130. [CrossRef]
22. Clifton-Ross, J.; Dale, A.; Newell, R. Frameworks and models for disseminating curated research outcomes to the public. *SAGE Open* **2019**, *9*, 2158244019840112. [CrossRef]
23. Holmes, K. Exhibition curation as practice-as-research performance historiography: An incomplete story of audience experience. *Stud. Theatre Perform.* **2024**, *44*, 306–326. [CrossRef]
24. Xu, D.; Zhang, W.; Zhang, C.; Mao, R.; Wang, C. Digitally enriched exhibitions: Perspectives from Museum professionals. *Tour. Manag.* **2024**, *105*, 104970. [CrossRef]
25. Philippopoulos, P.I.; Drivas, I.C.; Tselikas, N.D.; Koutrakis, K.N.; Melidi, E.; Kouis, D. A holistic approach for enhancing museum performance and visitor experience. *Sensors* **2024**, *24*, 966. [CrossRef] [PubMed]
26. Carrozzino, M.; Bruno, N.; Bergamasco, M. Designing interaction metaphors for Web3D cultural dissemination. *J. Cult. Herit.* **2013**, *14*, 146–155. [CrossRef]
27. Carpendale, S. Evaluating information visualizations. In *Information Visualization: Human-Centered Issues and Perspectives*; Springer: Berlin/Heidelberg, Germany, 2008; pp. 19–45. [CrossRef]
28. Card, S.K.; Mackinlay, J.; Shneiderman, B. *Readings in Information Visualization: Using Vision to Think*; Morgan Kaufmann: Burlington, MA, USA, 1999.

29. LaViola, J.J., Jr.; Kruijff, E.; McMahan, R.P.; Bowman, D.; Poupyrev, I.P. *3D User Interfaces: Theory and Practice*; Addison-Wesley Professional: Boston, MA, USA, 2017.
30. Diehl, C.; Martins, A.; Almeida, A.; Silva, T.; Ribeiro, Ó.; Santinha, G.; Rocha, N.; Silva, A.G. Defining recommendations to guide user interface design: Multimethod approach. *JMIR Hum. Factors* **2022**, *9*, e37894. [CrossRef] [PubMed]
31. Davies, J.; Welch, J.; Milward, D.; Harris, S. A formal, scalable approach to semantic interoperability. *Sci. Comput. Program.* **2020**, *192*, 102426. [CrossRef]
32. Hyvönen, E. *Publishing and Using Cultural Heritage Linked Data on the Semantic Web*; Morgan & Claypool Publishers: San Rafael, CA, USA, 2012; Volume 3.
33. Parry, R. *Recoding the Museum: Digital Heritage and the Technologies of Change*; Routledge: Oxfordshire, UK, 2007.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.