

Article

# Evaluating and Enhancing Museum Websites: Unlocking Insights for Accessibility, Usability, SEO, and Speed

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**Abstract:** The digital transformation of museums has elevated their websites from mere informational tools to dynamic platforms that foster cultural engagement, inclusivity, and preservation. This study evaluates the performance of 234 museum websites worldwide, focusing on critical dimensions such as accessibility, usability, SEO, and speed. By employing a comprehensive diagnostic framework of evaluation metrics, the research reveals disparities between mobile and desktop versions, highlights regional variations, and identifies key performance drivers. Generally, desktop sites outperform their mobile counterparts, underscoring the necessity for tailored optimization strategies that strike a balance between fast-loading, visually stable mobile pages and content-rich desktop experiences. A key contribution of this study is the development of an easy-to-adopt and inclusive evaluation framework that unites fragmented approaches, enabling museums of all sizes to enhance their digital presence. Furthermore, the research provides actionable insights for administrators, particularly those in resource-constrained institutions, through a cost-free, user-friendly toolkit that simplifies technical metrics and promotes internal staff capacity building in digital analytics. Ultimately, the findings help empower museums to bridge digital performance gaps while ensuring they continue to function as vibrant cultural hubs in a rapidly changing digital landscape.

**Keywords:** website; museum; metrics; evaluation; performance; accessibility; usability; SEO; speed; digital analytics



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## 1. Introduction

The digital transformation of museums has heralded a new era in which websites serve as essential gateways to cultural engagement and education, transcending geographical boundaries and redefining accessibility and inclusiveness [1]. As these digital platforms continue to evolve, they are moving beyond merely providing operational information; they have become immersive and interactive tools for audience engagement, featuring elements such as virtual tours, augmented reality, and high-resolution archival collections [2]. This evolution highlights the importance of museum websites as critical instruments for cultural preservation, inclusivity, and ongoing audience interaction in an increasingly interconnected digital landscape.

Yet, the potential of digital platforms remains inconsistently fulfilled, as many museum websites face challenges in achieving a balance between usability, accessibility, and technical quality. Research indicates ongoing problems, including low levels of adherence to accessibility standards, suboptimal content strategies, usability issues, and significant variations in website performance between mobile and desktop devices [3–5]. Additionally,

smaller and less renowned institutions often lack the resources or tailored guidance necessary to improve their digital presence, which exacerbates the divide between high-profile museums and their less prominent peers [6]. These disparities in digital performance not only restrict audience engagement but also risk marginalizing users with disabilities or limited access to high-speed internet, ultimately undermining the inclusive mission of cultural institutions.

In this respect, the primary objective of this study is to directly address these deficiencies by introducing a comprehensive and user-centered evaluation framework for museum websites that can be easily adopted by administrators. More specifically, by leveraging a global dataset and robust diagnostic tools, this effort evaluates critical dimensions, including accessibility, usability, speed, and search engine optimization metrics, to assess museum websites in an overall context. The findings aim to empower museums of all sizes to optimize their online platforms, bridging regional disparities and fostering inclusive, high-performing digital experiences through their websites.

The primary contributions of this study are as follows:

- It offers a comprehensive evaluation framework by presenting a holistic diagnostic framework for evaluating museum websites. It integrates metrics for accessibility, usability, SEO, and speed. This approach effectively addresses the fragmented nature of previous research, which frequently examined these dimensions in isolation.
- It fosters a globally inclusive and representative approach by developing a dataset of 234 museums across various geographical regions worldwide. By bridging the gap between high-profile institutions and smaller, resource-limited museums, the proposed inclusive methodology ensures that the findings are reflective of a multitude of contexts.
- It provides a dual optimization strategy through the findings, one that is specifically tailored to meet the distinct needs of mobile and desktop website versions. The research highlights the importance of layout stability and rapid content loading for mobile users. In contrast, it emphasizes the necessity of incorporating rich and interactive features to enhance the engagement for desktop users.
- It gives a clear and accessible explanation of technical metrics, enabling non-technical museum personnel to understand and execute improvements with assurance. By promoting digital analytics skills, the framework diminishes third-parties dependency while simultaneously enhancing internal competencies for sustained digital optimization.
- It offers a cost-effective diagnostic methodological framework designed to facilitate practical and accessible digital optimization for resource-constrained institutions. By democratizing access to digital enhancement strategies, this approach enables smaller museums to improve their web platforms without the hindrance of financial constraints. Such an initiative promotes equity in digital engagement and empowers these institutions to enhance their online presence and outreach efforts.

The relevant background is explored in the following section, highlighting the significance of museum websites and the efforts associated with the application of evaluation frameworks to these websites. This next section also articulates the research problem and the rationale for the necessary contribution. The third section describes the materials and methods, focusing on data collection, the metrics used and their explanation, and the data analysis techniques. The fourth section presents the results, while the fifth last section engages in discussion, addressing the key findings, theoretical and practical contributions, future directions, and limitations.

## 2. Related Background

### 2.1. Importance of Museum Websites

The significance of museum websites has become paramount in the era of digital transformation, acting as vibrant gateways that link cultural institutions with audiences across the globe. As museums adapt to the needs of a digitally oriented society, their websites provide far more than mere functionality. They serve as platforms for cultural information discovery, engagement, and innovation. These websites transcend geographical boundaries by incorporating advanced features such as virtual tours, interactive exhibits, and augmented reality experiences, inviting a worldwide audience to explore their collections [7]. These digital interfaces enhance the museum's outreach and redefine how cultural narratives are shared and preserved in a technology-driven world [8].

In terms of online visitor engagement with cultural content, a museum website with a compelling performance has the power to enhance visitor journeys, improving both their pre-visit and post-visit experiences. Before arriving at the museum, visitors depend on the website for essential information, such as operating hours, ticketing options, accessibility features, and detailed previews of exhibitions. These resources streamline the planning process and generate excitement and anticipation through virtual sneak peeks and engaging storytelling [9]. Once the visit concludes, the website serves as a digital extension of the physical experience. With usable online cultural heritage content that expresses usability, such as high-resolution digital archives, virtual replicas of exhibitions, and educational resources, visitors can revisit their favorite exhibits and deepen their understanding, ultimately fostering loyalty and sustained engagement. In addition to enhancing visitor experiences, museum websites serve as vital instruments for cultural preservation and inclusivity. By digitizing collections, these websites ensure that artifacts are safeguarded while their cultural information remains accessible to researchers, educators, and the public. By adhering to accessibility standards such as WCAG 2.1, websites actively promote inclusivity, ensuring that all users, including those with disabilities, can meaningfully engage with museum content [10].

Moreover, during periods of global disruption like the COVID-19 pandemic, museum websites demonstrated their resilience by providing access to cultural content despite physical closures, highlighting their essential role as digital lifelines for the arts and culture sector [11]. More specifically, during the pandemic, museums encountered an unprecedented challenge: the sudden closure of physical spaces necessitated a rapid transition from displaying physical objects to delivering entirely online experiences. This revolutionary shift urged cultural institutions to rethink their engagement strategies and emphasize digital innovation. Museum websites evolved into the primary channels for interaction, transforming into hubs for live-streamed tours, virtual workshops, and online exhibitions [12]. This period highlighted the essential role of websites as vital resources for cultural preservation and accessibility, enabling audiences worldwide to continue exploring, learning about, and connecting with heritage despite the physical barriers imposed by the pandemic.

Emerging as vital tools during the pandemic era, distinctive museum websites stand as enduring testaments to a cultural heritage organization's commitment to relevance and digital innovation. They showcase the organization's adeptness in adopting cutting-edge technologies for digital service delivery, skillfully marrying tradition with modernity. By prioritizing usability, accessibility, and technical excellence, museums can create online experiences that are informative and transformative. This transformative power solidifies their role as vital cultural and educational hubs in an ever-evolving digital landscape [13].

Building on the demonstrated importance of museum websites, it is evident that a well-designed website in terms of usability, accessibility, and discoverability is more than

a digital tool. It becomes a gateway for users to explore, learn, and form meaningful connections with history in ways that inspire and resonate over time.

## 2.2. Website Evaluation Frameworks

### 2.2.1. Usability and User Engagement

The development of engaging and user-centric museum websites is of paramount importance in attracting a diverse audience and providing a cohesive digital experience. Recent research underscores the efficacy of employing a variety of evaluation methodologies—spanning from established usability scales to sophisticated decision-making frameworks—in identifying obstacles and facilitating significant enhancements in website usability and user engagement. Huang and colleagues [14] evaluated and redesigned the Heyuan Dinosaur Museum website, using TRIZ theory to improve usability and user satisfaction. Their method included performance measurement, the System Usability Scale (SUS), and behavioral observation. The results highlight low usability despite high satisfaction with the website's visual design, leading to a redesign approach that significantly enhanced user satisfaction across all levels. Another evaluation approach comes from [15]. The researchers categorized user groups, focusing on the behaviors of the general public and non-professional users. Their investigation unveiled notably high bounce rates across various websites, leading to recommendations for targeted content strategies aimed at enhancing usability and, by extension, boosting user engagement.

In a broader context, Ma and Hu [16] employed the analytic hierarchy process (AHP) to assess the utility index of 115 national museum websites in China. Their findings revealed that content completeness and updating frequency were pivotal factors influencing user experience. Additionally, the analysis uncovered the pronounced technological and operational deficiencies prevalent in the majority of these websites. The AHP was also used to evaluate the Foshan Museum website, assigning weights to usability factors by combining behavioral data and user feedback in a systematic usability testing process. The findings identified significant issues in the information structure and key content gaps, which were addressed through iterative improvements validated by subsequent testing [17]. A closely related effort also came from [6], who examined two prominent Spanish museums websites. The authors found that website quality in terms of usability affects e-loyalty and trust among online visitors.

### 2.2.2. Accessibility and Inclusiveness

Accessibility to museums' digital presence is essential for fostering inclusivity and ensuring equitable access to cultural heritage for diverse user groups. It plays a crucial role in engaging all individuals, regardless of their backgrounds or abilities, enabling them to explore and appreciate cultural narratives and artifacts. Recent studies have identified significant challenges in achieving website accessibility compliance across different regions, highlighting common barriers and the urgent need for improved adherence to WCAG 2.1 standards. In India, for example, Pandey and Kumar [3] assessed the accessibility of 11 Indian museum websites against WCAG 2.1 standards using automated tools. Their results revealed low levels of compliance, characterized by low conformance levels, with the most frequent issues being inadequate text alternatives, poor color contrast, and missing labels. Similarly, Todorov and colleagues [5] utilized the WCAG 2.1 standard to examine the accessibility level of 30 Bulgarian museum websites. Their findings demonstrated substantial barriers for visually impaired users, including poor audio or text alternatives, insufficient metadata, and missing navigation aids. Over 80% of the websites failed to meet basic accessibility standards, even when offering features digital collections and virtual tours. Silva and Lopes [18] utilized a mixed-method approach, combining user testing

with automated evaluation tools to assess the accessibility of the Brazilian Museum of Arts and Crafts website. According to the authors, while the website showed some degree of compliance with established accessibility guidelines, significant deficiencies in areas such as textual descriptions and assistive navigation tools restricted overall inclusivity and accessibility.

### 2.2.3. Technical Performance and Speed

The digital transformation of cultural heritage institutions, including museums, has underscored the pivotal significance of website optimization in augmenting online traffic and user engagement [19]. Recent scholarly investigations stress the importance of implementing technical enhancements, structuring metadata effectively, and employing search engine optimization (SEO) methodologies to bolster online discoverability and visibility to elevate user satisfaction. These studies underscore that a comprehensive approach to digital infrastructure is essential for cultural institutions seeking to enhance their online presence and foster a more inclusive digital experience for diverse audiences. In line with this, ref. [20] proposed a methodology that involved the analysis of the content management system structure and its search capabilities, and the integration of metadata for the National Museum of Korea website. The results highlighted the need for significant improvements in terms of optimizing technical aspects and metadata structures that are capable of improving keyword search, region-based exploration, and, generally, the virtual exhibitions that the museum offers. Xylogianni and colleagues [21] examined the critical role of website speed in boosting user engagement for cultural heritage institutions, such as libraries, archives, and museums. Utilizing data from 121 websites, the authors employed statistical models to evaluate the factors affecting speed performance across both mobile and desktop platforms. The results indicate that optimizing server response time and reducing page size significantly increases speed scores and lowers bounce rates.

Rivera [22] examined organic SEO practices for museum websites in the United States and evaluated their effectiveness in enhancing online visibility. Through technical audits and the manual assessments of 214 websites, the research identifies common shortcomings in metadata optimization, structured data implementation, and technical SEO practices. The findings indicate that the adoption of schema.org markup and the refinement of SEO strategies can markedly improve search visibility. Meneses and colleagues [23] conducted a comprehensive analysis of structured data and outputs generated by SEO software, aiming to delineate the various user behaviors that occur across the stages of awareness, consideration, conversion, and loyalty. Their findings yield actionable insights that can significantly enhance strategies for optimizing user engagement and retention.

### 2.3. Problem Statement

Previous research has offered important insights into various aspects of optimizing museum websites, including usability, accessibility, technical performance, and SEO. However, there is still needed to address the fragmented and isolated nature of these efforts to better understand the overall challenges in optimizing museum websites. With the rapid advancement of digital transformation, a diagnostic evaluation approach for museum website performance has become increasingly critical [24]. Current studies often focus exclusively on individual cases or high-profile museums, leaving smaller and less renowned institutions largely overlooked. Regional research, especially in developing countries, often yields insights that are frequently inapplicable to museums in developed regions, and vice versa. Moreover, the fragmented approach to examining different website aspects—such as accessibility, usability, SEO, or speed—in isolation fails to capture the comprehensive picture needed to implement holistic improvements. Notably, existing

studies frequently neglect to identify and prioritize the key factors that most significantly influence website performance, leaving museum professionals without clear guidance on where to concentrate their efforts. Moreover, the prevalence of overly complex evaluation models further complicates practical implementation for museum staff, making it a daunting task. This fragmented and narrow focus highlights an urgent need for comprehensive, user-centered, and actionable research that enables museums of all sizes and contexts to enhance their digital presence. Such research should focus on the creation of genuinely inclusive, engaging, and high-performing online experiences [25].

Table 1 delineates the principal research gaps and highlights the necessary contributions required to effectively address the aforementioned deficiencies in the existing literature.

**Table 1.** Research gaps and recommended contributions for enhancing museum website performance.

Existing Approaches	Contribution Needed
Focus on individual cases or high-profile museums, neglecting smaller and less renowned institutions.	Broader research, encompassing a diverse range of museums, including smaller and less prominent institutions.
Regional research, often limited to developing countries, with no generalizable findings.	Comparative studies that bridge regional differences and provide globally applicable insights.
A fragmented approach in the investigation factors such as such as accessibility, usability, SEO, or speed in an isolated way and not as a holistic evaluation schema.	The development of a holistic diagnostic approach that integrates and evaluates all critical aspects of website performance.
Lack of identification and prioritization of key metrics influencing website performance compared to less impactful aspects.	Identifying and ranking the most impactful metrics for targeted and effective website improvement.
Overly complex evaluation models that are difficult for museum staff to implement.	Creation of practical, user-friendly evaluation framework tailored to museum staff.

To address these limitations, this study incorporates accessibility, usability, speed, and SEO metrics to provide a comprehensive evaluation framework for museum websites, offering actionable insights for enhancing digital performance across diverse institutions.

### 3. Materials and Methods

#### 3.1. Data Collection

In order to determine the museum cases to be included in this study, we built upon an existing dataset created by [26]. By expanding the original dataset, we increased the number of cases from 121 to 234, representing a substantial 94.2% growth and incorporating a broader and more diverse range of museums. This expansion was crafted to fulfill the necessity for more comprehensive research, ensuring that smaller and less prominent institutions are fairly represented alongside major museums. To accomplish this, the dataset utilized in this study was carefully curated to provide a representative and diverse selection of museums, capturing various dimensions crucial for a thorough understanding of website performance within the cultural heritage sector. The following selection criteria explain the rationale behind the choice of museum cases and their relevance to the study:

- *Geographic and global representation:* The selection of museums for this analysis encompasses a wide range of geographical regions, offering a comprehensive view of global trends and disparities in digital performance amid the ongoing digital transformation. This methodological approach deliberately includes institutions from both developed and developing nations, thereby elucidating regional variances in digital adoption rates and pathways.
- *Diversity of institution types:* The dataset encompasses diverse museum types based on an established categorization framework [27]. This includes art museums and

galleries; historical and cultural museums; archeological, anthropological and ethnographic museums; natural history, agricultural, and science and technology museums; and aquaria or zoos. Incorporating this variety allows the study to explore digital performance across different institutional focuses and visitor engagement strategies, adding depth to the analysis.

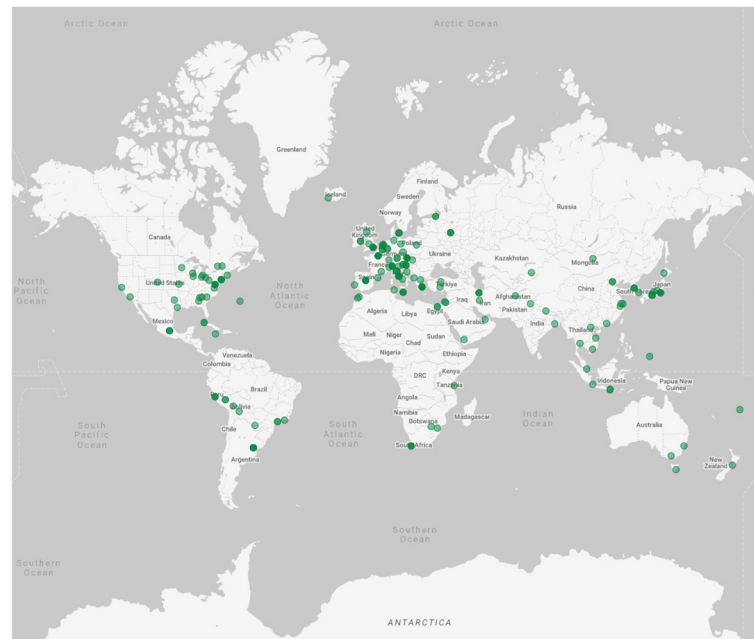
- *Publicly available digital presence:* This study focused solely on museums that have publicly accessible websites. This criterion ensures that data collection targets institutions with a confirmed online presence, enabling performance evaluation using standardized website assessment tools. Additionally, this approach provided a consistent methodology for assessing website performance across all museums, regardless of their type, location, or size.

During the initial data collection phase, we gathered each museum's official name and website domain to enable a thorough assessment of their digital performance. Additionally, the expanded dataset facilitated comparative analysis by incorporating museums from various regions, allowing us to gain insights into regional disparities and fostering a deeper understanding of global digital transformation trends. Figure 1 provides a visual representation of the geographic distribution of museums included in our study, which is presented as a world map bubble chart prepared using Google Looker Studio. Additionally, Figure 2 presents a bar chart depicting the number of museums per type as determined in this study.

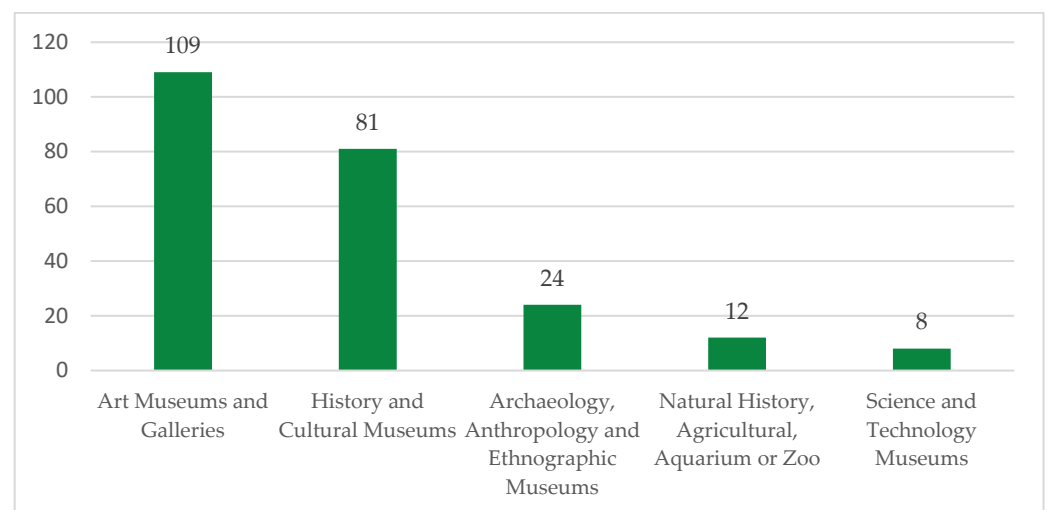
To assess the website performance of the 234 museums, we employed Google PageSpeed Insights (PSI), a tool chosen for its comprehensive features. PSI conducts an in-depth audit across various dimensions, including usability, accessibility, SEO, and speed, offering a holistic overview of website technical performance. It generates detailed reports highlighting specific areas for improvement, pinpointing particular sections of webpage code that need attention. Additionally, the tool provides actionable recommendations with thorough documentation and practical suggestions, empowering website administrators with the necessary guidance to improve their sites effectively. PSI also generates separate performance reports for mobile and desktop platforms, allowing for a nuanced understanding of how websites perform on different devices. Moreover, PSI's cost-free availability removes financial barriers, providing museum website administrators with equitable opportunity to conduct effective performance evaluations. This choice ensures a robust and practical assessment of museum websites, yielding actionable insights for digital enhancement.

For metrics retrieval, all data were manually collected. Although this process was time-consuming, it was deliberately chosen to enhance the accuracy and flexibility of our data. This method enabled us to uncover anomalies, contextual issues, and distinct patterns that automated tools might miss. By customizing this process to address specific site nuances, we reduced errors and enriched our analysis with qualitative observations and precise insights.

Finally, to ensure the reliability and validity of the data collected, and to address potential factors that may affect accuracy, such as fluctuations in internet connection stability, variations in device capabilities, and caching mechanism [28], a secondary manual audit was conducted. This audit, which covered 25% of the sample (58 out of 234 websites), revealed only minor discrepancies in the metrics, confirming the consistency and integrity of the original scores.



**Figure 1.** Geographic distribution of museums in the website performance evaluation conducted in this study.



**Figure 2.** Number of museums per type.

### 3.2. Metrics Involvement and Explanation

This subsection provides a detailed overview of the website performance metrics used in this study. Each metric is clearly defined, with its significance explained, addressing the need to identify and prioritize key aspects of effective website enhancement. Additionally, this documentation supports a practical, user-friendly evaluation framework for museum staff, offering the tools needed to improve their digital presence. This approach ensures transparency and facilitates informed decision-making throughout the evaluation process. Nine performance metrics were employed to evaluate the 234 museum websites, with separate scores for mobile and desktop versions. Table 2 summarizes the metrics and their explanations.



**Table 2.** Definitions of website evaluation metrics.

PageSpeed Insights Metrics	Explanation
Total Performance Score	This evaluates the performance of a webpage on mobile or desktop devices, emphasizing loading speed, responsiveness, and visual stability. It provides a score ranging from 0 to 100, which is categorized as poor (0–49), needs improvement (50–89), or good (90–100). This score is derived from a collection of several key metrics, which are detailed in the table below.
Accessibility Score	The Accessibility Score in PageSpeed Insights measures the effectiveness of a webpage in accommodating users with disabilities by adhering to best practices for usability and inclusivity. It evaluates aspects such as a proper navigation structure, readable text contrast, appropriately labeled elements, the use of ARIA roles and attributes, and compatibility with assistive technologies. A high score closer to 100 indicates that the page is optimized to meet the diverse needs of all users and vice versa.
Best Practices Score [29]	This measures the degree to which a webpage complies with established web development standards. This encompasses the adoption of contemporary web technologies, the utilization of optimized and efficient code, adherence to secure connection protocols, the proper implementation of essential meta tags, and the effective management of JavaScript. A high score signifies a secure, reliable, and well-optimized website.
SEO Score	This calculates how well a webpage is optimized in terms of search engine discoverability and ranking. It evaluates aspects such as the presence of meta descriptions, valid hreflang and canonical tags, descriptive link text, alt attributes for images, and proper indexing settings. A high score indicates effective search engine optimization practices for improved visibility.
First Contentful Paint (FCP) [30]	It measures the time it takes for visible content on a webpage—such as text, images, SVG elements, or non-white canvas elements—to appear on the screen after a user starts loading the page. To deliver a positive user experience, it is recommended that FCP occurs within 1.8 s or less.
Total Blocking Time (TBT) [31]	This measures the amount of time after the FCP during which the main thread is blocked, preventing the user from interacting with the webpage. If any task takes longer than 50 milliseconds, users may perceive delays, making the page feel slow or unresponsive. To ensure a proper user experience, webpages should aim for a Total Blocking Time of less than 200 milliseconds, particularly as regards their use on average mobile hardware.
Speed Index [32]	This estimates how quickly a webpage’s visual content becomes visible during loading. It analyzes snapshots of the loading process, with scores under 3.4 s considered fast, scores of 3.4–5.8 s considered moderate, and scores over 5.8 s considered slow.
Largest Contentful Paint [33]	This calculates the time to render the largest visible element in the viewport after navigation, starting from when the user first navigates to the page. For a good user experience, LCP should be 2.5 s or less, which measured at the 75th percentile across mobile and desktop users.
Cumulative Layout Shift [34]	This calculates the visual stability of a webpage by tracking unexpected shifts of visible elements during the page’s lifecycle. It captures how often and to what extent these shifts occur, which can negatively impact the user experience. A good CLS score value is 0.1 or less, ensuring a stable and predictable page layout for users.

Furthermore, to further illustrate the research dataset and how it was formulated, Table 3 presents representative performance data from three museums of the dataset as an example. On the first column from the left, the scores per metric are given and are separated between Desktop and Mobile. Each one of the three museums receives different scores per metric. These examples provide insights into the dataset’s characteristics and analytical techniques, offering readers a deeper understanding of the data’s relevance and implications within the context of museum studies and digital presence.

**Table 3.** Indicative performance metrics by platform for selected museum websites.

Scores	mak.at	chammuseum.vn	heritagemuseum.org
<i>Desktop</i>			
Total Performance Score	68	63	56
Accessibility	74	78	85
Best Practices	81	48	74
SEO	80	70	82
First Contentful Paint	0.7	1.8	2.7
Total Blocking Time	40	0	150
Speed Index	1.6	4	2.9
Largest Contentful Paint	2.5	3.2	6.3
Cumulative Layout Shift	0.305	0.131	0.002
<i>Mobile</i>			
Total Performance Score	35	29	48
Accessibility	79	66	84
Best Practices	81	44	70
SEO	92	74	83
First Contentful Paint	2.5	4.1	11.6
Total Blocking Time	650	120	330
Speed Index	5.8	12.7	9.6
Largest Contentful Paint	4.9	6	22.2
Cumulative Layout Shift	0.661	0.092	0.043

### 3.3. Data Analysis Methods

Descriptive statistics were employed to gain a foundational understanding of the dataset and to summarize its key properties, including central tendencies, variability, and distribution patterns.

We employed key statistical metrics—mean, median, minimum, maximum, standard deviation, kurtosis, and skewness—to analyze the dataset’s properties and distribution. The mean, median, minimum, and maximum capture central tendencies, while standard deviation reflects variability, showing how data points deviate from the mean. Skewness assesses distribution symmetry, highlighting whether data lean toward higher or lower values [35]. Kurtosis was used to examine “tailedness,” identifying outliers and improving the robustness of regression analyses [36]. Paired t-tests were conducted to compare desktop and mobile performance metrics, with *p*-values assessing the statistical significance of mean differences [37].

A pairwise regression analysis was conducted to identify the metrics that exerted the most significant influence on performance metrics for both mobile and desktop platforms, as well as those that exhibited a comparatively diminished effect. For pairwise linear regression models,  $R^2$ , *p*-values, and the F-statistic were key metrics. The  $R^2$  measures model works by explaining the variance in the dependent variable [38]. Then, *p*-values test the significance of relationships between variables [39], and the F-statistic evaluates the overall model significance, with higher values indicating stronger predictive capability [40]. Together, these metrics assess model performance and predictive reliability.

## 4. Results

### 4.1. Descriptive Analysis of Performance Metrics

The findings showcase intriguing patterns in the digital performance of museum websites, presenting areas of growth opportunities (Tables 4 and 5). On mobile platforms, museums demonstrate a commendable adherence to best practices, achieving the highest mean score of 89.15. Accessibility (mean: 83.03) and SEO (mean: 85.46) lag slightly behind, indicating areas where targeted improvements could enhance user inclusivity and search visibility. The negative skewness observed in mobile metrics—which is most pronounced in best practices (−1.57)—indicates that many institutions excel in these areas. However, the variability highlighted by the standard deviation points to the uneven adoption of best practices across the sector.

**Table 4.** Museum mobile website performance—generic metrics.

	Mobile Accessibility Score	Mobile Best Practices Score	Mobile SEO Score
Median	85	96	86
Mean	83.03	89.15	85.46
Std. Deviation	11.24	13.37	10.55
Skewness	−1.04	−1.57	−0.79
Kurtosis	1.84	2.36	0.59
Minimum	33	30	50
Maximum	100	100	100

**Table 5.** Museum desktop website performance—generic metrics.

	Desktop Accessibility Score	Desktop Best Practices Score	Desktop SEO Score
Median	85.00	96.00	83.00
Mean	82.59	88.90	85.35
Std. Deviation	11.46	13.75	10.17
Skewness	−1.02	−1.45	−0.33
Kurtosis	1.62	1.72	−0.41
Minimum	33	30	55
Maximum	100	100	100

Desktop performance reflects similar trends, with best practices achieving a mean score of 88.90, followed closely by accessibility (mean: 82.59) and SEO (mean: 85.35). The tighter distribution of SEO scores on desktop, evidenced by a near-normal skewness (−0.33), indicates that there is a higher degree of consistency with fewer outliers. The results reveal a critical balance between excellence and uniformity in museum websites. While museums have made significant progress in aligning with industry standards, placing greater emphasis on accessibility and SEO could enhance equity and visibility. Accessibility ensures that all users, particularly those with disabilities, have equitable access, while robust SEO practices improve online discoverability—a vital component for reaching wider audiences in the digital era [41].

Moreover, the variability in scores, as indicated by high standard deviations, reflects an inconsistent level of digital maturity across institutions. This underscores the necessity for sector-wide initiatives to bridge these gaps, such as via the development of shared digital resources or training programs for museum staff [42]. By fostering collaboration and building capacity across institutions, these initiatives lay the foundation for an integrated

digital optimization strategy that harmonizes technical standards with inclusivity and visibility. Such a strategy would enable museums to serve diverse user groups better while strengthening their online presence [43,44]. In addition, as demonstrated by the data presented in Tables 6 and 7, usability and speed metrics reveal considerable differences between mobile and desktop museum website performance. These disparities clearly highlight both priorities and opportunities for improvement in future optimization efforts.

**Table 6.** Mobile websites—usability and speed metrics.

	Total Mobile Performance Score	First Contentful Paint	Total Blocking Time	Speed Index	Largest Contentful Paint	Cumulative Layout Shift
Median	43.00	4.00	165.00	10.30	12.15	0.03
Mean	43.31	5.49	270.25	13.74	16.91	0.15
Std. Deviation	19.44	5.05	328.47	12.04	14.93	0.25
Skewness	0.44	3.69	1.79	2.58	2.17	2.23
Kurtosis	0.35	21.55	5.60	8.94	5.85	4.69
Minimum	4.00	0.90	0	0.90	0.90	0
Maximum	100	47.10	2300	75.80	94.10	1.20

**Table 7.** Desktop websites—usability and speed metrics.

	Total Desktop Performance Score	First Contentful Paint	Total Blocking Time	Speed Index	Largest Contentful Paint	Cumulative Layout Shift
Median	64	1.3	30	3.10	3.20	0.01
Mean	64.62	2.46	99.54	4.83	5.80	0.14
Std. Deviation	20.31	3.37	166.53	5.49	7.64	0.26
Skewness	−0.22	3.57	2.35	3.17	3.57	3.25
Kurtosis	−0.51	14.98	5.29	12.40	14.73	13.91
Minimum	14	0.30	0	0.40	0.40	0
Maximum	100	24.10	810	37.80	51.40	1.79

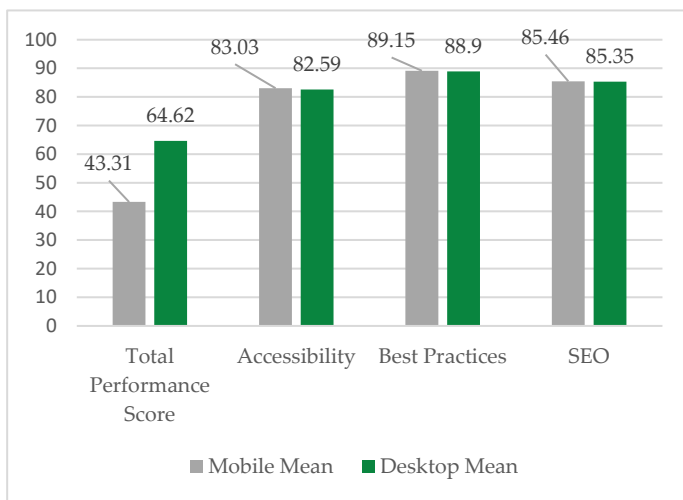
Mobile websites face considerable challenges, as evidenced by a low average performance score of 43.31 and substantial variability (SD: 19.44). These results indicate that there are inconsistent user experiences across different institutions. Key metrics such as First Contentful Paint (mean: 5.49 s) and Total Blocking Time (mean: 270.25 ms) suggest that users often have to wait long for content to load—a critical issue in an era where speed and efficiency on the web are crucial. The high kurtosis (21.55) and skewness (3.69) for First Contentful Paint indicate that although some websites perform well, others fall short of meeting essential performance standards. However, the low average Cumulative Layout Shift (mean: 0.15) signifies that museums are making notable progress in ensuring visual stability, which is a commendable step toward enhancing mobile usability [34].

Desktop performance, in contrast, offers a more optimistic outlook, with a higher average score of 64.62 and smoother overall functionality. Key metrics, such as Total Blocking Time (mean: 99.54 ms) and Largest Contentful Paint (mean: 5.80 s), reflect relatively faster and more responsive user experiences. Moreover, the negative skewness (−0.22) in desktop scores suggests that many websites perform above the average, reflecting a strong emphasis on optimizing desktop platforms. However, the average First Contentful Paint time of 2.46 s indicates there is still room for improvement in delivering prompt

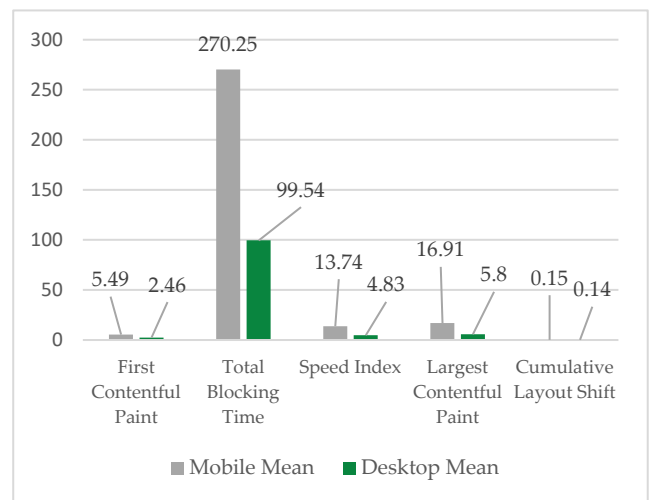
visual feedback. The noticeable disparity between mobile and desktop metrics reveals a critical gap: while museums are excelling on desktop, they must address the shortcomings on mobile platforms, where user engagement is increasingly concentrated. Addressing this gap through a mobile-first strategy and enhanced performance initiatives could help museums remain relevant and accessible to contemporary audiences [41]. In Table 8, a comprehensive comparison of mobile and desktop metrics is presented. The results were determined through *p*-values derived from paired t-tests, assessing the statistical significance of the differences observed. These comparisons are also graphically presented in Figure 3a,b, facilitating a clearer understanding of the differences in the mean values of the metrics examined.

Table 8. Usability and spread metrics: mean comparisons.

Paired Samples t-Test			
Measurement	Mobile Mean	Desktop Mean	<i>p</i> -Value
Total Performance Score	43.31	64.62	<0.001 (sig)
Accessibility	83.03	82.59	0.184 (non-sig)
Best Practices	89.15	88.90	0.514 (non-sig)
SEO	85.46	85.35	0.697 (non-sig)
First Contentful Paint	5.49	2.46	<0.001 (sig)
Total Blocking Time	270.25	99.54	<0.001 (sig)
Speed Index	13.74	4.83	<0.001 (sig)
Largest Contentful Paint	16.91	5.80	<0.001 (sig)
Cumulative Layout Shift	0.15	0.14	0.554 (non-sig)



(a)



(b)

Figure 3. (a) Generic metrics comparison; (b) usability and speed metrics comparison.

The analysis indicates that four out of the nine metrics—Accessibility, Best Practices, SEO, and Cumulative Layout Shift—show no statistically significant differences in the mean values between the mobile and desktop versions of the websites. This result suggests that the comparable performance of the mobile and desktop versions is more likely the result of intentional design or optimization changes rather than random variation. This consistent performance across platforms reflects a foundational commitment to universal design and web standards. However, a closer look at the slightly higher mean scores for Best Practices (mobile: 89.15; desktop: 88.90) and SEO (mobile: 85.46; desktop: 85.35) imply

a tendency to prioritize technical compliance over user-centric features, such as accessibility. This nuanced emphasis reflects a need for museums to align their technical optimization strategies more closely with inclusive design practices, as highlighted by [45].

However, the paired t-test reveals significant differences in other key metrics, emphasizing performance gaps that disproportionately affect mobile platforms. Desktop websites consistently outperform their mobile counterparts in terms of Total Performance Score, First Contentful Paint, Total Blocking Time, Speed Index, and Largest Contentful Paint. For example, mobile platforms show a significantly higher Total Blocking Time (270.25 ms) compared to desktops (99.54 ms), suggesting that mobile users may encounter longer delays in interactivity. By ensuring quicker load times and improved mobile responsiveness, museums can directly boost user satisfaction and engagement, which are essential for contemporary digital audiences.

#### 4.2. Predictive Modeling of Performance Metrics

The regression analysis identified the key metrics influencing mobile performance scores, as presented in Table 9. Specifically, First Contentful Paint (Coefficient = 0.899,  $R^2 = 0.054$ ,  $p$ -value < 0.001) and Cumulative Layout Shift (Coefficient = 0.769,  $R^2 = 0.256$ ,  $p$ -value < 0.001) emerge as significant predictors of performance. These findings indicate the importance of fast-loading and visually stable pages, which are particularly crucial for museum visitors seeking exhibit details or event schedules on the go. Delays in rendering the first visible content or experiencing unstable layouts can be frustrating and may drive users away. In contrast, Total Blocking Time (TBT) shows no significant correlation with mobile performance (Coefficient = 0.001,  $R^2 = 0.001$ ,  $p$ -value = 0.701), suggesting that delays in interactivity may not be crucial for enhancing overall mobile performance scores.

**Table 9.** Regression analysis results: predicted contributions of Mobile PageSpeed Insights Metrics to Total Performance Score.

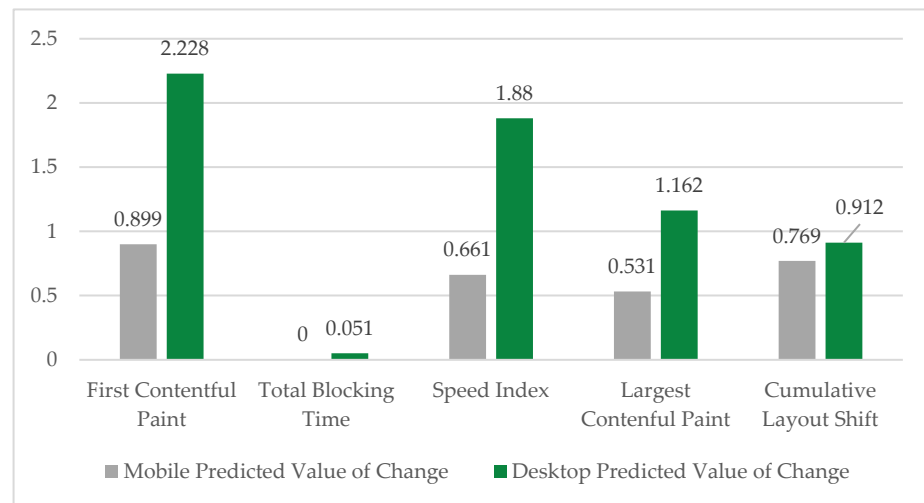
Variable	Coefficient	$R^2$	F-Statistic	p-Value
Constant (Mobile Total Performance Score)	48.248			
First Contentful Paint	0.899	0.054	13.371	<0.001 (sig)
Constant	43.716			
Total Blocking Time	0.001	0.001	0.148	0.701 (non-sig)
Constant	52.393			
Speed Index	0.661	0.168	46.685	<0.001 (sig)
Constant	52.298			
Largest Contentful Paint	0.531	0.167	46.386	<0.001 (sig)
Constant	49.165			
Cumulative Layout Shift	0.769	0.256	79.909	<0.001 (sig)

Table 10 presents the regression equation output for desktop performance metrics. Contentful Paint (LCP) (Coefficient = 0.912,  $R^2 = 0.213$ ,  $p$ -value < 0.001), along with First Contentful Paint (FCP) and Cumulative Layout Shift (CLS), are the primary contributors to total desktop performance. The Speed Index (Coefficient = 1.880,  $R^2 = 0.258$ ,  $p$ -value) and Total Blocking Time (TBT) (Coefficient = 0.051,  $R^2 = 0.172$ ,  $p$ -value < 0.001) are also highly significant. These results emphasize the necessity for museums to optimize interactive and resource-intensive elements for desktop users, who are more likely to engage deeply with a site's content. The findings support previous research [46], which highlights the dual role of museum websites: serving as quick information hubs on mobile devices, while functioning as rich interactive cultural portals on desktops.

**Table 10.** Regression analysis results: predicted contributions of desktop PageSpeed Insights Metrics to Total Performance Score.

Variable	Coefficient	R <sup>2</sup>	F-Statistic	p-Value
Constant (Desktop Total Performance Score)	70.093			
First Contentful Paint	2.228	0.137	36.726	<0.001 (sig)
Constant	69.659			
Total Blocking Time	0.051	0.172	48.283	<0.001 (sig)
Constant	73.698			
Speed Index	1.880	0.258	80.851	<0.001 (sig)
Constant	71.353			
Largest Contentful Paint	1.162	0.191	54.757	<0.001 (sig)
Constant	69.517			
Cumulative Layout Shift	0.912	0.213	62.626	<0.001 (sig)

Figure 4 provides a summary of the regression equation outputs, highlighting the predicted Coefficient values and their variations between desktop and mobile performance metrics. The results clearly indicate that museum website administrators must prioritize mobile performance optimization, as mobile regression results indicate lower predicted values of change in all metrics. By focusing on enhancing layout stability and improving initial load times, museums can create a seamless and inviting mobile browsing experience, especially for visitors seeking quick access to information such as exhibit details or event schedules. The significant impact of First Contentful Paint (FCP) and Cumulative Layout Shift (CLS) on mobile performance underscores the necessity for fast-loading and visually stable pages.



**Figure 4.** Predicted contribution of each metric to total mobile and desktop website performance.

For desktop platforms, the more substantial contribution of Largest Contentful Paint (LCP) and the Speed Index highlight the need to prioritize the optimization of content-rich pages and interactive features. These improvements enhance deeper user engagement through functionalities like virtual tours and detailed exhibit explorations, enhancing the overall cultural experience on desktop devices. Moreover, these insights advocate for a dual optimization strategy for museum website administrators to streamline performance for mobile users, while enhancing interactivity and responsiveness on desktop platforms. This balanced approach not only elevates user satisfaction but also aligns with museums' missions to make culture and history accessible and engaging to diverse audiences [47].

## 5. Discussion

### 5.1. Major Findings

This study conducted a comprehensive analysis of 234 museum websites from various regions globally to evaluate their overall performance across mobile and desktop platforms. The key dimensions assessed were accessibility, usability, search engine optimization (SEO), and loading speed. To this end, a robust three-tier methodology comprising data collection, metrics selection, and descriptive and predictive data analysis was developed and implemented.

The results provide critical insights into the performance of museum websites, highlighting significant disparities between mobile and desktop platforms and identifying areas for improvement. Desktop platforms showed significantly higher average performance scores (mean: 64.62) compared to mobile platforms (mean: 43.31), with notable differences in critical metrics such as Total Blocking Time (desktop: 99.54 ms; mobile: 270.25 ms) and Largest Contentful Paint (desktop: 5.80 s; mobile: 5.49 s). Conversely, mobile websites demonstrated lower First Contentful Paint scores (mean: 2.46 s), indicating slower load times that may impede the user interactivity level.

Also, notable variabilities within the metrics were depicted, as evidenced by a high standard deviation of 19.44 in Mobile Total Performance Scores, highlighting inconsistencies in digital maturity across museums. Metrics such as Cumulative Layout Shift (mean: 0.15 for mobile) and Speed Index (mean: 1.88 for desktop) emerged as pivotal in shaping user experiences. These findings underscore the necessity for a dual optimization strategy: mobile platforms should concentrate on layout stability and faster loading times, while desktop platforms need to enhance content-rich and interactive features.

The regression analysis further identified key drivers of mobile and desktop platforms' performance. For mobile platforms, First Contentful Paint (Coefficient = 0.899,  $R^2 = 0.054$ ,  $p < 0.001$ ) and Cumulative Layout Shift (Coefficient = 0.769,  $R^2 = 0.256$ ,  $p < 0.001$ ) emerged as the most significant predictors, stressing the importance of fast-loading and visually stable pages. In contrast, Total Blocking Time (Coefficient = 0.001,  $R^2 = 0.001$ ,  $p = 0.701$ ) had no significant impact, suggesting that delays in interactivity are not as critical for overall mobile performance. For desktop platforms, the analysis indicated the importance of Largest Contentful Paint (Coefficient = 0.912,  $R^2 = 0.213$ ,  $p < 0.001$ ) and Speed Index (Coefficient = 1.880,  $R^2 = 0.258$ ,  $p < 0.001$ ), reflecting the need for optimized resource loading and responsive design for content-heavy pages. Desktop users, who are more likely to engage with detailed and interactive content, benefit from faster and more responsive performances.

Overall, these findings offer museum administrators actionable guidance for optimizing website performance: it is possible to enhance layout stability and load times for mobile platforms while improving content delivery and interactivity for desktop platforms. This dual strategy aligns with the evolving demands of digital audiences, enabling museums to position themselves as accessible, innovative, and engaging cultural hubs. By implementing these recommendations, museums can enhance user satisfaction and extend their reach to diverse global audiences in the digital era.

### 5.2. Theoretical Contributions

This study offers significant theoretical advancements by addressing critical gaps identified in previous research. Firstly, it enhances our understanding of museum website performance by incorporating smaller institutions into the analysis—a demographic approach often overlooked, as pointed out by earlier studies [48]. The expanded dataset, comprising 234 museums, ensures that the insights obtained reflect diverse contexts, effectively bridging the gap between high-profile institutions and smaller regional museums.



Secondly, the study provides a comparative evaluation of museum websites across various regions, yielding globally applicable insights into trends in digital transformation. By highlighting regional disparities in adherence to accessibility standards—such as the low WCAG 2.1 compliance levels, as also detailed by prior efforts [3,5]—this research emphasizes the necessity of promoting a standardized global approach while remaining attuned to regional challenges and constraints.

Lastly, the research develops a holistic diagnostic framework by integrating usability, accessibility, SEO, and technical performance metrics into a cohesive approach. Unlike fragmented approaches that evaluate these dimensions in isolation [14,16], the proposed methodology acknowledges their interdependence and assesses their collective impact on user engagement. The statistical techniques employed—such as regression analysis and paired t-tests—further identify and rank the most influential metrics, providing a comprehensive understanding of the drivers of digital performance.

### 5.3. Practical Contributions

This study equips museum administrators with effective and practical tools to enhance their digital presence and user engagement while being highly cost-efficient. Central to this approach is a no-cost methodological framework that leverages tools that, despite requiring no financial outlay, provide detailed and actionable performance insights. This strategy is transformative for smaller or less-resourced museums, dismantling financial barriers and ensuring equal access to essential digital performance evaluations [49].

The methodological framework proposed in this study is designed to maximize adaptability by museum staff. Covering aspects such as accessibility, SEO, usability, and speed metrics all in one assessment framework, museum administrators are guided through each component clearly and organized. This approach not only makes the framework accessible to non-technical personnel but also facilitates the swift identification and implementation of actionable improvements. Similar strategies have effectively bridged digital maturity gaps, especially in cultural institutions with limited IT resources [25,50]. As a result, even the most resource-constrained museums can achieve momentous steps to enhance their websites.

In addition to its structural elements, the framework enhances its utility by offering a clear, jargon-free glossary of key website metrics. Terms around website performance and optimization—often perceived as complex technical jargon by museum staff—unfolded into straightforward explanations in this research. This approach enables museum administrators to confidently interpret and act on performance data, cultivating a culture of digital self-sufficiency. By equipping staff with essential digital literacy skills, museums can diminish their reliance on external consultants, thereby conserving resources while simultaneously building internal knowledge capacity and skills [51].

Inclusivity is another cornerstone of this framework, as it explores the accessibility compliance of the examined websites. By advocating for adherence to WCAG 2.1 standards, the study reinforces the importance of ensuring that websites are technically optimized and accessible to all users, regardless of abilities. And actually, this focus on inclusivity aligns perfectly with museums' mission to democratize cultural heritage content for all users [52,53].

Concluding the practicability of this research, the current study provides museum administrators with a financially accessible, user-friendly, and strategically aligned toolkit designed to enhance their digital presence through their websites. The methodology's no-cost approach, combined with its systematic structure and capacity-building resources, ensures ease of adoption across museums of various sizes and contexts. This study motivates museums to make advancements in an increasingly digital landscape while remaining

committed to their cultural missions by simplifying complex evaluation processes, improving digital analytics capability, and prioritizing inclusivity.

#### 5.4. Future Steps and Limitations

This study explored website performance analytics by analyzing 234 museums around the globe to assess accessibility, usability, SEO, and speed. To extend this research, further investigation is required on how museums leverage another vehicle to promote their services—that is, social media platforms—in order to enhance user engagement and interaction with their cultural content and services. To address this, we have initiated the collection of social media analytics and metrics from these 234 institutions. This involves examining the level of completeness of metadata in their profiles and analyzing the text content of their posts to gain insights into their content and themes and the levels of engagement they generate. A similar methodology has proven effective in previous efforts focused on closely related organizations [54].

The existing approach offers a thorough framework for evaluating museum websites, focusing on accessibility, usability, SEO, and speed. However, incorporating additional feedback from relevant stakeholders through structured quantitative or qualitative questionnaires would further enhance our understanding of museum website performance in these areas. In other words, future research should integrate analytical metrics with stakeholder input to improve precision in identifying and prioritizing optimization opportunities. It is also noted that additional investigation is necessary to evaluate the adaptability and usability of the proposed evaluation framework in real-world contexts. This would involve collecting website performance data, conducting diagnostic analyses to assess the current state, and formulating a strategy for prioritizing needs and optimizing museum websites based on the results.

Lastly, the framework proposed in this study presents a structured, scalable, and financially accessible approach to enhancing museum websites. Nevertheless, it is crucial to acknowledge the inherent limitations of technology and online tools in confronting the broader challenges of inclusiveness, equity, and democracy within museums. While digital tools can potentially improve accessibility and engagement for museum visitors, they may inadvertently exacerbate marginalization and exclusion for individuals with limited access to reliable devices or internet connections, including older adults and children from economically disadvantaged backgrounds [55]. This situation underscores a significant paradox: while digital transformation holds promise, it can unintentionally reinforce existing inequities rather than dismantle them.

Consequently, museums should exercise caution in perceiving digital solutions as an inclusivity and equity panacea. In addition to optimizing websites and digital tools, museums must prioritize complementary initiatives to address these systemic barriers. Such initiatives could include in-person programs, outreach efforts to underserved communities, and the development of inclusive environments that celebrate a diversity of experiences [56]. These non-digital strategies ensure that museums serve as universally accessible cultural hubs, rather than perpetuating digital divides. Effectively bridging these gaps will require future efforts that extend well beyond the parameters of this study. Research integrating broader social, economic, and technological contexts will be crucial for addressing these challenges comprehensively. Such an approach will enable museums to foster genuine inclusivity by leveraging the strengths of digital tools while addressing their inherent limitations.

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