Accessibility By Design

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Abstract. While digital accessibility is a fundamental human right, modern web systems often fail to meet legal standards due to inadequate developer tools and persistent barriers for users with visual impairments. This research proposes an **Accessibility by Design** framework that integrates accessibility considerations into both the development and consumption phases of web systems. The framework is composed of two complementary components: an AI-assisted development environment that leverages Large Language Models to support developers in auditing and generating accessible web components and a web-based multimodal system that translates visual STEM data into multisensory representations through sonification. The study evaluates how integrating accessibility considerations into product design enhances usability while ensuring equal access for all users regardless of their abilities.

Keywords: Web Accessibility · Sonification · LLM.

1 Introduction

Digital accessibility is a fundamental human right, ensuring that all users can interact with technologies and services on equal terms. Although this principle is formally protected by the United Nations Convention on the Rights of Persons with Disabilities [8], practical implementation remains a challenge. According to a report of Web Accessibility in Mind (WebAIM), more than 95% of the world's top one million home pages still fail basic accessibility tests [12]. The major reason for this scenario is that accessibility is still often seen as an additional requirement rather than an integral part of the engineering process. However, as highlighted by the principle of Universal Design, designing for diverse user needs actually enhances usability for everyone, included search engines and AI agents [5]. From this perspective, accessibility should not be viewed merely as a matter of compliance, but as an opportunity to improve the overall quality of the web.

Developers often struggle to correctly interpret and implement current guidelines. Furthermore, even when digital content is available online, users with visual impairments still face significant barriers to accessing highly visual information, particularly in Science, Technology, Engineering, Mathematics (STEM) domains, where charts, graphs, and mathematical functions are central. Current tools usually address content creation and content consumption separately, without offering an integrated perspective that connects the two.

This research addresses these challenges by proposing an **Accessibility By Design** framework to integrate accessibility into both the production and use of

digital systems. The framework follows two complementary research directions. The first focuses on content creation, supporting developers with a tool based on Large Language Models (LLMs) to help them assess, fix, and generate web content that complies with current accessibility standards. The second focuses on content consumption, enabling end-users — particularly those with visual impairments — to access and interact with STEM content through alternative interaction modalities. The goal is to design a web-based mathematical suite that represents functions, bar charts, and pie charts through visual and auditory modalities, enabling users to access information in the way that best suits their needs. This research aims to make accessibility a core principle of web engineering rather than an afterthought or an extra constraint. The expected outcome is a unified framework that demonstrates the value of treating accessibility as a first-class requirement throughout the development process.

2 Research Questions

This research aims to investigate how an **Accessibility by Design** framework can reduce digital barriers by supporting both the creators and consumers of web content. The research is structured around three research questions:

RQ1: Supporting the production of accessible web content. How can LLMs be used to support developers in assessing, fixing, and generating web content that complies with current accessibility standards? In particular, how can techniques such as Retrieval-Augmented Generation (RAG) and fine-tuning improve the reliability of these systems in real development contexts?

RQ2: Supporting access to visual STEM content on the web. How can sonification approaches developed for mobile environments be extended to support web visual STEM content, e. g., mathematical functions, bar charts, and pie charts? Furthermore, how can these approaches be integrated into a unified web-based mathematical suite based on auditory feedback?

RQ3: Evaluation of the Integrated Framework. To what extent can the proposed Accessibility by Design framework, combining AI-driven developer support and multimodal web-native interfaces, improve accessibility across both content creation and content use compared to traditional approaches?

3 Background and Related Work

The W3C provides the technical foundations of web accessibility through the Web Content Accessibility Guidelines (WCAGs). WCAGs are organised in 4 core principles: Perceivable, Operable, Understandable, and Robust (POUR). Each principle contains a set of testable success criteria categorised into 3 levels (A, AA, and AAA) [10]. Despite this, their practical adoption remains challenging.

Several jurisdictions have introduced binding legal requirements. In the US, *Section 508 of the Rehabilitation Act* mandates accessibility for federal agencies' electronic and information technology, while in the EU, the *European Accessibility Act* (Directive 2019/882) defines common requirements for digital products

and services across member states [9],[2]. These regulations increase the need for tools that help developers correctly apply accessibility standards.

The adoption of these legal requirements led to the study of how LLMs can support activities such as generating descriptive alternative text and identifying accessibility issues that are difficult to detect through traditional analysis [7]. Prior work suggests that LLMs can provide better context-related feedback than traditional tools for the detection of rule-based violations [1], [4].

Despite this potential, important reliability concerns remain: LLMs may hallucinate, identifying issues that are not in the source code or correcting snippets that do not present any violations. These limitations reduce trust in LLM-based accessibility support and highlight the need for approaches that can better ground model outputs in verified technical knowledge. This gap motivates investigating techniques such as RAG and fine-tuning to improve the reliability of AI-assisted accessibility support, as addressed in **RQ1**.

Accessibility in digital environments also depends on the presence of interaction modalities that make complex content perceivable to different users. This issue is particularly evident in STEM domains, where information is frequently conveyed through highly visual representations such as charts and mathematical functions [11]. Screen readers often provide limited support for communicating spatial relationships and structural properties in this type of content. In recent years, web-based interactive environments, such as Jupyter notebooks, have become widely adopted in STEM education, but they still present severe accessibility challenges for blind and visually impaired users [6], both in terms of content structure and accessibility of generated data representations.

To address these limitations, previous research has explored multimodal approaches based on sonification and haptic feedback. These techniques can provide alternative ways of representing complex visual information through sound and touch. In this context, the author's previous work, *GraficiAccessibili* [3], investigated the use of such techniques in a mobile environment for the study of mathematical functions. However, an open challenge remains in extending these solutions to a unified web-native environment that can support a broader range of STEM content. This gap motivates **RQ2**, which investigates how sonification approaches can be adapted for the web and integrated into a mathematical suite to enable accessible interaction with functions and statistical charts.

4 Proposed Methodology

This section describes the current research components—namely, the development of the *SviluppAbile* extension and the web-based evolution of *GraficiAccessibili*—and presents the unified framework that integrates them within the proposed Accessibility by Design core.

4.1 LLM-Based Accessibility Assistant

The first component of this research addresses the content creation dimension. *SviluppAbile* is a browser extension designed to support accessibility within the

Web Engineering lifecycle. Unlike general-purpose AI models, *SviluppAbile* implements a RAG pipeline grounded in WCAGs 2.2 and W3C techniques. The goal is to improve the reliability of LLM outputs by grounding them in verified accessibility knowledge and making the generated feedback traceable to recognised standards. The tool operates in two complementary modes:

- **Assessment Mode:** analyses existing HTML, identifies potential accessibility violations, and provides explanations and remediation strategies linked to violations identified by traditional tools.
- **Develop Mode:** supports generation of code compliant with the standards and explanations of best practices to follow for developers.

We also investigates fine-tuning techniques as a complementary strategy to further improve the reliability and accuracy of model outputs. A comparative evaluation will be conducted to assess how RAG, fine-tuning, and their combination influence the quality of accessibility feedback generated by *SviluppAbile*.

This component addresses **RQ1** by investigating how LLM-based systems can support developers to assess and generate accessible web content.

4.2 GraficiAccessibili on Web

The second component addresses the content consumption, through the web-native evolution of *GraficiAccessibili* [3] to generalise the sonification engine beyond mathematical functions and extend it to bar charts and pie charts, completing the development of the mathematical suite introduced in Section 1.

This component addresses **RQ2** by investigating how multimodal access to visual STEM content can be integrated into a web-native environment.

4.3 The Integrated Accessibility By Design Framework

The synthesis of these two components forms the proposed **Accessibility by Design** framework (Fig. 1). The framework connects accessibility at the level of content creation with accessibility at the level of content consumption, thus reflecting the two complementary dimensions of the research.

On the developer side, *SviluppAbile* supports the production of accessible web content by combining standards-based knowledge, contextual explanations, and AI-assisted guidance. On the end-user side, *GraficiAccessibili* supports access to visual STEM information through sonification and other multisensory interaction channels. Taken together, these two components operationalise the Accessibility by Design vision by addressing accessibility across both content creation and content consumption.

To investigate these research directions, the methodology combines system development with comparative evaluation. For **RQ1**, *SviluppAbile* will be assessed in terms of its ability to identify, explain, and generate accessible web content in alignment with WCAG requirements. For **RQ2**, the web-based evolution of *GraficiAccessibili* will be evaluated with respect to its support for auditory interaction with mathematical functions and statistical charts. For **RQ3**,

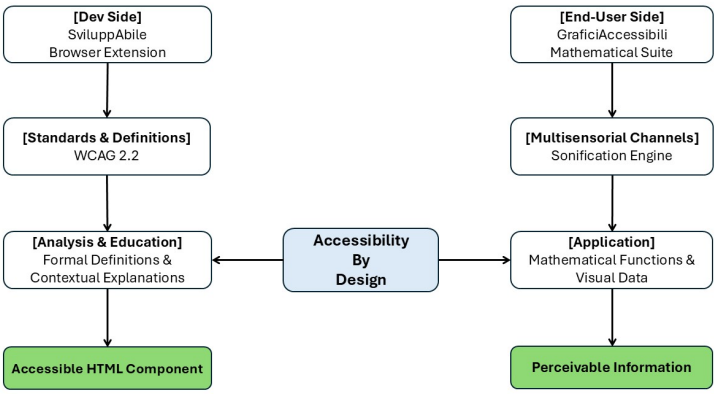


Fig. 1. The proposed Accessibility by Design framework.

the integrated framework will be examined as a unified accessibility approach spanning both content creation and consumption, compared with traditional reactive workflows.

From a Web Engineering perspective, integrating accessibility requirements into the development process improves the quality of web systems for all users. Web solutions compliant with WCAGs include features that benefit the broader user base, such as adequate color contrast, semantic markup that improves both readability and maintainability, and clearly structured content. Similarly, a mathematical suite designed to make STEM content accessible to users with visual impairments becomes a more effective educational tool for all students.

5 Conclusion and Future Work

This paper presented an **Accessibility by Design** research framework aimed at integrating accessibility into both the production and use of digital systems. The proposed study is structured around two complementary research directions: supporting developers in the creation of accessible web content, and enabling multimodal access to visual STEM information for end users. Together, these directions aim to position accessibility as a core principle of Web Engineering rather than as a reactive adaptation. The current stage of the research includes the development of the *SviluppAbile* browser extension and the web-based evolution of *GraficiAccessibili*. These two components provide the foundation for investigating how accessibility can be addressed across both content creation and content consumption within a unified framework. Future work will focus on completing the development of these tools and evaluating their effectiveness.

On the developer side, *SviluppAbile* will be assessed on its ability to identify accessibility violations, explain them clearly, and generate web content that complies with WCAG requirements. To support this evaluation, we plan to develop

a web-based dataset of content-specific accessibility violations and compare the system's performance with that of traditional accessibility tools.

On the end-user side, *GraficiAccessibili* will be extended to support bar and pie charts, with effectiveness evaluated through controlled listening tasks involving both sighted users and users with visual impairments. These tasks will assess information perception via sonification. Moreover, we aim to collaborate with schools to identify features and support the suite's adoption.

Finally, the integrated framework will be examined as a whole to explore its potential to improve accessibility practices across both content creation and use, compared with traditional approaches.

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