NEW METHODS AND ALGORITHMS FOR TESTING WEB ACCESSIBILITY

Thesis of Ph.D. dissertation

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1. Overview of Web Accessibility, its Objective and Current Limitations

According to the World Wide Web Consortium (W3C) report, web accessibility is a broad and extensible term associated with people who have disabilities, incompetent skills, or situational-induced impairment [1]. This initiative's objective is to ensure accessibility of digital platforms which means people with special needs should be able to access, navigate, interact, and contribute to the information that is available on the Web/Internet, electronic resources/materials, and computers. Generally, web or internet platforms broadly refer to the digital services of webpages whereas accessible web refers to the design and development of webpages in a manner that is effective for people with disabilities and without disabilities [2].

In general, webpage is a digital platform for sharing a variety of information (healthcare, education, e-commerce, etc.) with people. However, sometimes, these digital resources are not properly organized (such as the presence of broken links, out-of-date content, dilated images, etc.). From the perspective of digital services, digital resources should be organized to make them accessible and barrier-free to people with disabilities [3]. From this perspective, accessibility ensurement of digital platforms or webpages has been addressed multiple times by the Web Accessibility Initiative (WAI), and they set their mission to coordinate international, technical, and human efforts to improve and ensure web accessibility widely [4]. With this mission in mind, WAI launched a set of accessibility guidelines called Web Content Accessibility Guidelines (WCAGs) [5][6]. However, the web accessibility guidelines suggest that a webpage should have an advanced design and the latest technology for development so that people with disabilities can perceive, understand, navigate, and interact with the web more efficiently [7].

Although W3C and WAI initiated their great effort in the area of web accessibility, a few recent studies showed that the majority of

webpages even fail to maintain the basic accessibility requirements or minimum standards of accessibility [8][9]. As a result, people with disabilities experience several difficulties with web access. For example, web content information might be difficult to read and understand the meaning, placement of the user interface elements might be difficult to identify or remember, and some interactive designs (dropdown menu, sub tasks, landing page, etc.) might make the content partially or completely inaccessible. Besides, as the accessibility problems are distinct according to the type of disability, thus the problems or difficulties might vary from person to person and in different situations. Among several scenarios of difficulties, more particularly people with vision problems have difficulties understanding content that is written in very small font and specific theme (italic, and bolded). People with color blindness have difficulties recognizing specific colors, and people with cognitive difficulties have issues understanding the meaning of some complex or advanced words, notations, abbreviations, and alerts. Also, people with motion difficulties have issues with scrolling and pointing dropdown menu. In that case, people with disabilities are forced to spend more time on webpages to find their required information than people without disabilities. Therefore, the ensurement of accessibility of online information is a crucial aspect for technologists and researchers. With this aim, numerous research has been conducted focusing on how the web platform can be completely accessible to the community.

Addressing this concern, most of the conducted studies focused on the area of statistical analysis of web accessibility, and tools and applications development for measuring web accessibility. Here, statistical analysis of web accessibility refers to studies that focus on incorporating statistical measurement to determine the accessibility of a particular webpage. Besides, accessibility measurement tools and application development refer to the complete development of a particular approach or process to evaluate webpages to determine their accessibility. The tool development process can be automated or

a hybrid process. In an automated process, the accessibility measurement can either incorporate existing automated accessibility testing tools or a completely new automated tool can be developed for measuring accessibility. Besides, the hybrid testing process allows to incorporation of both automated tools and human perception together to measure the accessibility of the webpages. However, for webpage accessibility investigation tool design and development methods, the number of studies related to hybrid and automated evaluation processes is limited compared to statistical analysis due to lack of clarity, poor authenticity, and higher additional costs for investigation.

Besides, the studies for the development of hybrid and automated webpage accessibility testing processes are not significant compared to the other processes such as accessibility testing using existing automated tools. In addition, those studies found in the area of web accessibility tool design and development process have major issues related to the engineering aspects. Majority of the accessibility testing tools largely neglect advanced engineering assets into their consideration. Due to the lack of advanced engineering assets consideration, studies also found that majority of the existing tools or evaluation approaches are not useful to the end users which hinders their effectiveness in the community. Therefore, this introduces the importance of investigating different web accessibility evaluation processes and tool development approaches to determine an effective method and framework addressing how advanced engineering aspects can be integrated into the evaluation and development process to effectively validate webpage accessibility.

2. Research Objectives

Nowadays, web designers and developers are trying to incorporate several complex functionalities (e.g., dynamic, drop-down menu) and components (e.g., images, videos) into their web pages to make them

more interactive. Though these interactive functionalities are prominent to attract more people, they limit the accessibility concept for users with disabilities [10][11]. Therefore, nowadays, the demand for an effective tool has increased in the community to evaluate these interactive components in terms of their accessibility. Thus, it is increasingly important to evaluate several existing accessibility testing processes to determine their possible vulnerabilities and by addressing those vulnerabilities, propose an effective accessibility testing approach to validate the accessibility of the webpages. To achieve this purpose, the objective of this research is five-fold as follows:

- **Objective 1:** To understand, evaluate, and determine the strengths and limitations of the existing web accessibility evaluation approaches. This objective corresponds to the R-Q1.
- **Objective 2:** To minimize the finding limitations and improve the effectiveness of the hybrid web accessibility evaluation result, propose multiple effective hybrid web accessibility evaluation approaches. This objective corresponds to the R-Q2.
- **Objective 3:** To minimize the finding limitations and improve the effectiveness of the automated web accessibility evaluation result, propose an effective automated web content accessibility evaluation framework. This objective corresponds to the R-Q3.
- **Objective 4:** Following the proposed automated evaluation framework, develop an automated web content accessibility evaluation tool or environment for automatically validating webpage accessibility. This objective corresponds to the R-Q4.

- **Objective 5:** To determine the effectiveness of the developed automated evaluation tool, validate the developed tool by comparing it with existing models using their functional properties, and conduct a user study. This objective corresponds to the R-Q5.

3. Research Questions and Hypotheses

To achieve the previous-mentioned objectives, five research questions have been followed throughout the research. All the considered and answered research questions with their hypothesis are the following:

R-Q1: What are the challenges and drawbacks of the existing web accessibility testing process?

- **H-1:** Several issues associated with the effectiveness of the existing approaches make the evaluation process biased.

R-Q2: How can we improve the effectiveness of the hybrid web content accessibility testing process to address its current limitations?

- **H-2:** Incorporating several techniques such as involvement of user and expert testing, the concept of variable magnitude alternation, and Machine Learning (ML) techniques can be helpful to improve the effectiveness of the hybrid web content accessibility testing process.

R-Q3: How can we improve the effectiveness of the automated web accessibility evaluation process to address the limitations of the available automated web accessibility testing tools?

- **H-3:** The design and development process could be facilitated by the incorporation of a wide range of elements, including suitable guidelines, user and expert requirements, and advanced engineering techniques to increase the

effectiveness of the automated web accessibility evaluation process.

R-Q4: How can we increase the effectiveness of an automated web content accessibility assessment tool focusing on advanced engineering techniques?

- **H-4:** The enhancement of the tool's effectiveness may be greatly impacted by implementing separate algorithmic evaluations for arbitrary and non-arbitrary items focusing on semantic approaches by considering advanced engineering techniques such as Natural Language Processing (NLP).

R-Q5: How can the progress made with the developed tool be verified in terms of its effectiveness aspects?

- **H-5:** The effectiveness of the developed tool can be determined and represented by its functional properties. Results of user evaluations may also be useful in providing an actual scenario of effective components.

4. Hybrid Web Content Accessibility Evaluation Methods

According to the state-of-the-art literature, crowdsourcing and heuristic approaches are the two main branches of the hybrid testing or evaluation process. The crowdsourcing approaches generally allow for the integration of both automated testing (incorporating automated tools) and human evaluation (performed by hiring people including experts and users) to evaluate the accessibility of the web. Besides, heuristic approaches generally enable only human inspection in various ways to evaluate the accessibility of the web. From our empirical analysis and personal observation, crowdsourcing approaches are effective compared to heuristic approaches as

heuristic approaches only allow humans to evaluate which limits the evaluation process to a certain number of checkpoints, and assessment features, require higher cost, and might not be time effective solutions. Therefore, for the hybrid evaluation process, the objective of this thesis is to focus on crowdsourcing approaches to facilitate the accessibility evaluation process of web content.

Generally, existing crowdsourcing approaches are not free of limitations. Most of the existing crowdsourcing approaches are limited to the incorporation of i) lack of user and expert assessment, ii) consideration of a limited number of accessibility and usability criteria, iii) difficulty in the task distribution process, iv) not time effective, and v) not cost-effective that might hamper the evaluation process and limit the advancement of their developed crowdsourcing system. Addressing those issues, the aim of this research is to present three new crowdsourcing evaluation methods for the web content accessibility evaluation process that can help to improve the existing limitations and facilitate the evaluation process. The proposed three new crowdsourcing evaluation methods are **(i)** Integrated approach, **(ii)** Variable magnitude approach, and **(iii)** Machine Learning-based approach.

4.1 Integrated approach

Generally, the objective of the proposed integrated approach is to integrate both automated and human evaluation processes considering multiple automated tools implementation with user and expert assessment focusing on accessibility and usability criteria. As the majority of the existing approaches only focused on the automated tools without considering user and expert opinion, thus, integrating both aspects might improve the evaluation result. The proposed approach is divided into two steps: in step 1, evaluation is performed through multiple automated web accessibility testing tools (Mauve, Nibbler, WAVE, and WEB accessibility), and in step 2, evaluation is performed through human observation through questionnaires (such

as system usability testing and expert testing). To validate the proposed integrated method and perform the experimentation, the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) related government webpages have been chosen from different countries of Europe and Asia to understand their accessibility for people with disabilities.

From the evaluation results by the integrated approach, at first, a few webpages were accessible through automatic evaluation tools (Mauve++, Nibbler, WAVE, WEB accessibility). However, after going through questionnaire-based human judgment (system usability and expert testing), some inaccessible functionalities have been found in the tested webpages that were marked as accessible from the automatic testing. Regarding the user testing and expert testing, the quality of each webpage can be determined which is not possible to determine through any automatic testing tool. Through the automatic tool, it is only possible to identify whether the webpage has passed or failed the accessibility testing. With the automatic tools, it was unable to detect these issues and sometimes failed to produce the appropriate research output. Thus, human observation is effective in identifying the unreported problems of automatic tools. Regarding the user (SUS testing) and expert testing, neither of the webpages has manual font resize functionality, which could be a problem for people with poor vision. Some webpages have no accessibility option when using the TAB key. This webpage is not accessible to people who have learning disabilities. Although, some webpages have keyboard/TAB key accessibility, not for all the buttons or sub-menus, making the webpage inaccessible. Some webpages are not in English, and there are no translation options.

Additionally, a few of the webpages have a color deficiency, and it is hard to separate the links and buttons. Therefore, human judgment helps to find unexplored issues that are not possible through automatic tools that depict the effectiveness and the potentiality of the proposed integrated approach.

4.2 Variable magnitude approach

In past literature, a number of studies suggested the variable magnitude approach as a hybrid approach for web accessibility evaluation as it has effectiveness in identifying the accessibility of webpages in depth. According to their suggestions, Kuppusamy and Balaji [12] computed the accessibility barrier of several webpages through a variable-magnitude approach. They computed the accessibility barrier of several webpages through a variable-magnitude approach, considering two automated tools (AChecker and WAVE) output. Their proposed approach was effective; however, some limitations have been found that could reduce the effectiveness of their evaluated results. For example, for severity-factor selection, they chose a constant value of 0.1, which should be applicable for all the variables; however, they did not incorporate the severity factor for the initial variable (likely error, error). In other cases, the dimension of the input set of two algorithms was different (3:2), which might lead to an inappropriate calculation of the overall score. In addition, for different assessment parameters, they did not classify the dependent and independent parameters and their potentiality. For example, among known errors, likely errors, and potential errors, they did not address which error potentially reduces the accessibility or prime factor for the inaccessible scenario. Treating the three errors collectively might not be effective in identifying the actual accessibility scenario of webpages.

Addressing all of these aspects, I proposed a variable-magnitude approach to improve the evaluation results by minimizing the addressed issues. To do so, the proposed variable magnitude approach considers the evaluation results of two automated tools (Mauve++ and TAW) as input variables and calculates the accessibility score by altering the weight of the input variables, based on their importance, and integrating multiple variables' results to compute the final score. To classify the computed score in assessing the accessibility of the evaluated webpages, mathematical statistics, such as threshold

measurement, are employed. Furthermore, expert evaluation has been incorporated to evaluate the selected webpages to justify the computed score. According to the computed accessibility ratio by the proposed variable magnitude approach, the observation outcome is that the majority of the webpage's accessibility score is between the range of $\alpha = 0$ to <40 which depicts that they have low accessibility scores and are not accessible for people with disabilities. It represents a poor concern in the context of universal accessibility. Besides, two webpages have accessibility scores between the range of $\alpha = 40$ to <70, that determined as likely accessible, and one webpage has an accessible score between the range of $\alpha = 70$ to =<100, that determined as potentially accessible. The analysis results show the need for universal accessibility. Besides, from the expert analysis results, it can be concluded that the webpage designers and developers did not properly comply with the web content accessibility guidelines. Frequently, web designers and developers ignored the accessibility guidelines during development, even though the associated accessibility issues could have been easily fixed.

4.3 Machine Learning-based approach

Nowadays, web researchers have shown their active participation in considering machine learning (ML) methods to evaluate the quality and usability of webpages. By addressing the potential of ML approaches in web platforms, the prime aim of this section is to propose an ML approach for performing accessibility evaluation of web platforms. From the existing literature, the existing web accessibility evaluation approaches incorporate some specific attributes of webpages according to the Web Content Accessibility Guidelines (WCAG) to evaluate their accessibility status. Though the latest version of WCAG 2.2 [13] is a complete guideline for accessibility features, it has limited consideration about some issues with people with disabilities such as whether the webpage is active or deactivated, webpage has a manual text size adjustment option,

manual font family adjustment option, manual color adjustment option, user information requirement, CAPTCHA issues, the usefulness of internal/external links, used images, inserted video and audio content. As these features are not directly possible to evaluate in an automatic manner, WCAG does not provide a clear indication about these aspects though without considering these aspects, it is not possible to ensure complete accessibility of the developed webpages.

In that manner, the prime focus of this study is to evaluate webpages considering these additional criteria through ML algorithms and compute the overall accessibility score based on the selected additional criteria. The overall objective of this work is to observe the performance of the selected two ML classifiers (Random Forest (RF), and Decision Tree (DT)) to identify its effectiveness and then evaluate webpage accessibility according to the classification result. The prime challenges of this work were related to the prepared dataset as there is no dataset that has been found that evaluated webpages according to ten additional criteria. Thus, to conduct this work, a custom dataset is used that is prepared according to the ten aspects. For dataset preparation, a preliminary survey was conducted to understand the importance of the considered ten (10) criteria in terms of their effectiveness to the people with disabilities to represent the accessibility of the webpages. After obtaining the dataset, two ML algorithms have been applied to perform the experimentation.

The experiment result shows that the classification performance of the RF classifier is more significant than the DT classifier. The average accessibility score shows that Eotvos Lorand University has higher accessibility features (according to the selected features in this research work) than other university webpages. However, the computed score of other selected university webpages was very poor which represents that most of the selected university webpages are not accessible to people with disabilities in terms of the selected aspects/features. To improve the accessibility in accordance with the selected aspects, the selected university webpages need to improve their quality to ensure the complete accessibility objective. In

addition, concerning the performance of ML classifiers or models, it is interesting to address that ML classifiers or models are significant in the evaluation of the accessibility of university webpages.

5. Automated Web Content Accessibility Evaluation Methods

In the branch of automated web content accessibility evaluation methods, first, an inclusive automated accessibility testing framework has proposed considering the determined aspects from an extensive literature review that can facilitate the improvement of the available limitations of automated accessibility testing systems. After that an automated web content accessibility testing tool is developed following the proposed framework.

5.1 An Inclusive Framework for Automated Web Content Accessibility Evaluation

The proposed accessibility evaluation framework demonstrates five aspects considering several criteria to improve ambiguities, such as accessibility guidelines, user and expert suggestion, guideline simplification, automated testing, and issue identification and visualization. As the proposed approach focuses on a wide array of aspects including guidelines, additional criteria, evaluation result computation, visualization, etc. thus, it could be useful in facilitating the evaluation process and representing the computed results as reliable, acceptable, and fair. Also, compared to the existing system, the aspects addressed in the proposed system are not considered in the existing system which makes the proposed system distinctive. Besides, the proposed framework will be helpful for web practitioners and web researchers to understand the web evaluation process.

According to the listed several existing shortcomings from extensive literature, the overall observation is that the main aspects

leading to incorrect perception, encoding, and development of the accessibility evaluation tool are:

- Understanding difficulties of natural language formatted web content accessibility guidelines,
- Limited consideration of user requirements and expert suggestions,
- Lack of semantic concern.

These addressed issues make the evaluation results less credible and less acceptable. Most of the accessibility testing tools only check a specific number of WCAG success criteria which is around 50% of the total guidelines. As a result, it restricted the evaluation process, and the overall evaluation result might be inaccurate. As many web accessibility guidelines cannot be assessed automatically, they do not specify whether guidelines require user/expert testing or not. This also could be a cause of incorrect calculation of matrices and evaluation report formulation. Without incorporating the user's requirements/opinions and expert suggestions during the development of accessibility testing tools, the evaluation process may overlook some crucial aspects and inadvertently inflate the final accessibility score. Besides, a lack of consideration of semantic aspects may reduce the effectiveness of the evaluated results. Therefore, to minimize such issues, an accessibility aspects framework for automated web accessibility testing has been presented considering the following aspects that could help the development procedure and improve the evaluation process with accurate results.

- Simplifying the updated web content accessibility guidelines to represent the guideline knowledge in the easiest and most effective manner.
- Incorporating all success criteria in the evaluation process to make the evaluation results more effective while improving the fairness of the evaluated result.

- Incorporating user requirements/opinions with expert suggestions during the evaluation process as an additional evaluation criterion.
- Incorporating separate complexity analysis algorithms for textual feature, and non-textual feature analysis focusing on semantic aspects to improve the effectiveness of the evaluated result.
- Categorizing the evaluated guidelines in terms of user evaluation and expert evaluation when the guideline is not applicable for automatic evaluation.
- Displaying the evaluation result with the overall accessibility score along with specific accessibility scores for each disability type.

5.2 Automated Tool (WCAEE) Development and Implementation

Following the proposed framework, the developed WCAEE tool consists of four phases: (1) modeling the structural elements to facilitate the structuring of the guidelines and user requirements; (2) conducting a complexity analysis by loading the webpage and implementing three distinct complexity analysis algorithms; (3) formulating the report to provide an overall evaluation statistics that includes feedback and results related to each checkpoint of the implemented guidelines, as well as information on conformance level, impairment types, and improvement direction through four distinct window views; and (4) visualizing the report through various graphical analysis (graphs, charts, and other visual representations).

During the development process, standard web content accessibility guidelines and user assessments or requirements are considered for determining structural elements as these aspects provide a detailed view of important variables, also known as webpage objects, which are regarded as prime assets for evaluating webpage accessibility. The most recent version of the widely accepted

web content accessibility guidelines (WCAG 2.2) is evaluated, and a user study has been conducted to ascertain their requirements and assess the associated objects. In that case, it directs us to understand how web content accessibility guidelines and user requirements help to determine the structural elements to improve the accessibility issues or complexity. From guideline modeling, 28 objects or structural elements have been found that relate to 51 of the 87 WCAG 2.2 success criteria that are inherently evaluable. Based on expert knowledge, the remaining 36 success criteria need to be manually assessed. The identified 28 variables are classified into non-textual elements and textual elements. Besides, after assessing experts' suggestions, 10 additional variables have been identified that are crucial to consider in the proposed web accessibility evaluation process to address the identified twelve criteria

An algorithmic evaluation was carried out to analyze the complexity of particular web elements considering the accessibility perspective. The developed tool technically performs the accessibility evaluation based on three different algorithms: (**Algo.1**) Non-Text Complexity Analysis Algorithm; (**Algo.2**) Text Complexity Analysis Algorithm; and (**Algo.3**) Additional Criteria Validation Algorithm. The Text Complexity Analysis Algorithm assessed the complexity of the webpage's textual components, while the Non-Text Complexity Analysis Algorithm assessed the difficulty of the non-textual elements of the tested webpage. Besides, the Additional Criteria Validation Algorithm highlights the complexity of the interactive components of the tested page. To evaluate the accessibility of a particular webpage, the web page's URL is first validated in the WCAEE platform to determine its accessibility. Once the URL has been validated, it is sent to an HTML parser (in this case, Beautiful Soup) to parse the HTML code and convert it into the HTML Document Object Model (DOM) structure. The full HTML source code is represented by the DOM structure as a tree structure view, which may be utilized to navigate the HTML elements in accordance with the required HTML tags. To assess the complexity of the

corresponding elements that refer to various online objects, three distinct algorithms have been implemented. The evaluation results is presented through generated report based on the output of the complexity analysis using three different algorithms, and graphical representation (a number of data visualization techniques) to make the report effective, interactive, and helpful to the end user.

For implementing the developed WCAEE model, sublime text editor has been considered as a development framework and Python programming language to write the script to implement the proposed algorithms. The Windows 10 version has been taken into consideration which runs on the eighth-generation Intel Core i7 processor. The Tkinter package has been utilized to design user interfaces and numerous window views, as it is the most often used Python graphical user interface (GUI) library that enables the efficient creation of GUI programs. Additionally, an object-oriented interface such as the Tk GUI toolkit enables the integration of several objects into the user interface, which aids in creating and representing an interactive user interface for the user. A number of Python libraries have been used to traverse the tested webpage, parse the HTML code, extract the information such as elements and attributes, and carry out the full evaluation.

5.3 Automated Tool (WCAEE) Validation

To evaluate the developed WCAEE tool and to validate the accessibility evaluation report and computed accessibility score using the proposed tool, a two-phase experimental evaluation has been conducted. First, in the user-centric study, at first, the participants were asked to rate a sample of twenty (20) webpages based on their understanding or preference in terms of accessibility perspective. Second, the same sample of webpages was evaluated through the developed WCAEE tool to formulate their accessibility report. Then, user ratings were further compared with the accessibility scores computed by the WCAEE tool for the same sample of 20 webpages.

From this two-phase evaluation, it can be concluded that the WCAEE tool could predict the accessibility score that could align with the participants' perception and have the potential to predict the accessibility of a specific tested webpage because the majority of the webpage's accessibility status was similar according to the user-given score and the optimally computed score by the tool.

6. New Scientific Results

In this thesis, different approaches have been studied to mitigate the existing issues related to the evaluation of web content accessibility. In the following part, the new scientific results have been summarized considering three different thesis groups.

Thesis group-I: Web Content Accessibility Testing process considering advanced engineering aspects

In this thesis group, I investigated several proposed solutions for accessibility evaluation to identify frequently arising issues that limit the effectiveness of their development. According to the observation of my conducted research, it can be stated that:

Thesis-1: There are a few reference architectures for referring to accessible web design, development, and evaluation processes. {\color{blue}Most frameworks do not consider aspects related to cost and feasibility, such as human input cost and the quality of inputs in terms of level of expertise, consistency, cost, and generality of results across different disabilities}. Also, most frameworks focus on accessibility improvement for people with color vision deficiency and an accessibility testing and refinement process for the early phase of design and development. Besides, frameworks that consider only non-expert users raise inappropriate feedback regarding the wide spectrum of disabilities.

Sub-thesis-1: It would be beneficial to develop other reference architectures focusing on other contributing areas to solving the three problems: (a) Framework for the developer to identify and implement accessibility features to address accessibility issues, (b) Easy methods to understand and ensure accessibility requirements concerning every type of disability during the development phase, and (c) Updated automatic accessibility testing protocols incorporating the latest WCAG standards rules.

Sub-thesis-2: To overcome these problems, it can be noted that developing new methods and tools focusing on an accessibility evaluation strategy considering several aspects might help to improve the effectiveness of the further proposed solutions, such as: (a) Guideline selection, (b) User and expert suggestion consideration, (c) Guideline visualization, (d) Listing several webpage features that require special focus during tool development, and (e) Acceptable accessibility issue identification and visualization process.

The corresponding publications of this thesis group (I) are **A1, A9.**

Thesis group-II: Proposing Hybrid Web Content Accessibility Testing process using integrated techniques, variable magnitude approach, and ML techniques.

In this thesis group, I proposed three new hybrid web content accessibility testing approaches that have the potential to improve the effectiveness of the web accessibility evaluation process, which might be helpful for web practitioners in improving the accessibility of their webpages in the future. Based on the result of this thesis group, I formulate three theses as follows:

In the integrated approach,

Thesis-2: I improved the accessibility assessment process of web content by proposing an integrated approach that incorporates several automated evaluation tools, and a user and expert assessment based

on questionnaires. The proposed integrated approach is validated through experimental results, considering official websites related to COVID-19. The experimental result showed that integrating multiple automated testing tools and allowing user and expert assessment is crucial to improve the effectiveness of the evaluation result.

In the variable magnitude approach,

Thesis-3: I improved the effectiveness of the hybrid web content accessibility evaluation result by proposing a variable magnitude approach, considering the output of multiple automated evaluation tools to measure the accessibility scores of webpages. The proposed variable magnitude approach considers the evaluation results of two automated tools as input variables, calculates the accessibility score by altering the input variables' weight according to their importance, and integrates the results of multiple variables to calculate the final score. The proposed variable-magnitude approach is validated by incorporating expert evaluation and experimental results, considering the webpages of hospitals and clinics. Expert evaluation and experimental results show that the proposed variable magnitude approach is effective in properly identifying the accessibility status of the tested webpages.

In the machine learning-based approach,

Thesis-4: I emphasized the improvement of the hybrid web content accessibility evaluation result by proposing a Machine Learning (ML) approach considering ten additional evaluation criteria beyond the latest version of WCAG 2.2. The proposed ML approach was validated by training a model using a custom dataset that has been prepared according to the selected additional ten aspects obtained from user testing and incorporating two ML techniques (Random Forest (RF) and Decision Tree (DT)) to improve the effectiveness of the evaluated results. The proposed ML approach is experimented with considering the university webpage. The experimental results

show that the proposed ML approach is significant in the web testing domain and able to represent the actual accessibility insights of the tested webpages in terms of the additional evaluation criteria.

The corresponding publications of this thesis group (II) are **A2, A3, A4, A5, A6, A7.**

Thesis group-III: Developing Automated Web Content Accessibility Testing tool using knowledge simplification and advanced engineering techniques

In this thesis group, the work has been presented with a two-fold objective. At first, I proposed an automated web content accessibility evaluation framework to facilitate the accessibility evaluation process of webpages. To facilitate the evaluation process, I incorporated a guideline modeling approach that helps to simplify the natural text guideline into a logical format. Furthermore, according to the proposed framework, I developed an automated accessibility testing tool that considers a wide array of aspects in the evaluation process to improve the effectiveness of the evaluated results. Based on the outcome of this thesis group, I have formulated two theses as follows:

Thesis-5: I proposed an automated accessibility evaluation framework addressing several accessibility aspects such as (i) Simplifying the updated web content accessibility guidelines, (ii) Incorporating all success criteria in the evaluation process, (iii) Incorporating user requirements/opinions with expert suggestions, (iv) Incorporating separate complexity analysis algorithms for textual feature, and non-textual feature, (v) Categorizing the evaluated guidelines in terms of user evaluation and expert evaluation, and (vi) Displaying the evaluation result with the overall accessibility score to improve the evaluation results by mitigating the limitations of existing solutions. The proposed framework is validated by comparing it with existing automated solutions, considering their functional properties.

Thesis-6: I proposed a straightforward yet precise model that assesses webpage accessibility by taking into account common features of the structural and visual elements of webpages that are part of the HTML Document Object Model (DOM) structure. To develop the proposed model as a real-life accessibility testing tool, three distinct algorithms have been implemented to analyze web features/objects, considering both semantic and non-semantic aspects. The developed tool, namely Web Content Accessibility Evaluation Environment (WCAEE) is compared to other tools (that already exist) considering several functional characteristics or properties and experimental work with user study. This two-phase evaluation result shows that the developed tool has several advanced properties and the potential to predict the accessibility issues of the tested webpage.

The corresponding publications of this thesis group (III) are **A8, A9, A10, A11, A12, A13, A14, A15.**

6. Publication Related to the Thesis

[A1] Jinat Ara, Cecilia Sik-Lanyi, and Arpad Kelemen, "Accessibility Engineering in Web Evaluation Process: A Systematic Literature Review", Universal Access in the Information Society, Springer, 2023; pp. 1-34, https://doi.org/10.1007/s10209-023-00967-2. (**Impact Factor: 2.1**).

[A2] Jinat Ara and Cecilia Sik Lanyi, "Accessibility Evaluation of COVID-19 Information Websites across Europe". IEEE 34th Neumann Colloquium (NC), pp. 126-133. IEEE, (2021).

[A3] Jinat Ara and Cecilia Sik Lanyi, Investigation of COVID-19 Vaccine Information Websites across Europe and Asia Using Automated Accessibility Protocols. *International Journal of Environmental Research and Public Health*. 2022; 19(5):2867. https://doi.org/10.3390/ijerph19052867. (**Impact Factor: 3.390**).

[A4] Jinat Ara, Cecilia Sik-Lanyi, and Arpad Kelemen, "An integrated variable magnitude approach for accessibility evaluation of healthcare institute webpages", Applied Science, 2023; 13(2):932. https://doi.org/10.3390/app13020932. (**Impact Factor:2.5**).

[A5] Jinat Ara and Cecilia Sik-Lanyi, "Accessibility evaluation of healthcare webpages in Hungary using accessibility barrier computation algorithm", 1st IEEE International Conference on Internet of Digital Reality (IoD), 23-24 June, 2022, Gyor, Hungary, DOI: 10.1109/IoD55468.2022.9986974

[A6] Jinat Ara and Cecilia Sik-Lanyi, "Webpage accessibility evaluation using Machine Learning Technique", 14th IEEE International Conference on Cognitive Infocommunications (CogInfoCom), 2023, Budapest, Hungary, 10.1109/CogInfoCom59411.2023.10397496

[A7] Jinat Ara, and Cecilia Sik-Lanyi, "Computation of Accessibility Score of Educational Institute Webpages using Machine Learning Approaches", Infocommunications Journal, Joint Special Issue on Cognitive Infocommunications and Cognitive Aspects of Virtual Reality, 2024, pp. 49-57, https://doi.org/10.36244/ICJ.2024.5.6, **(Impact Factor: 1.16).**

[A8] Jinat Ara and Cecilia Sik-Lanyi, "Artificial Intelligent in Web Accessibility: potentials and possible challenges". International Academic Conference on Engineering, Transport, IT and Artificial Intelligence, 5-6 August 2022, Vienna, Austria.

[A9] Jinat Ara, Cecilia Sik-Lanyi, Arpad Kelemen, and Tibor Guzsvinecz "An Inclusive Framework for Automated Web Content Accessibility Evaluation", Universal Access in the Information Society, Springer, 2024, 1-27. DOI: https://doi.org/10.1007/s10209-024-01164-5. **(Impact Factor: 2.1)**.

[A10] Jinat Ara and Cecilia Sik-Lanyi, "Algorithmic Evaluation: Accessibility of Assistive Technology Webpage Content", 1st IEEE

International Conference on Internet of Digital Reality (IoD), 23-24 June, 2022, Gyor, Hungary, DOI: 10.1109/IoD55468.2022.9987021

[A11] Jinat Ara and Cecilia Sik-Lanyi, "AccGuideLiner: Towards a Modelling Approach of Web Accessibility Requirements following WCAG 2.2", In 2023 IEEE International Conference on Smart Information Systems and Technologies (SIST), Kazakhstan, 4-6 May 2023, pp. 10-15, 10.1109/SIST58284.2023.10223541

[A12] Jinat Ara and Cecilia Sik-Lanyi, "Towards developing a framework for automated accessibility evaluation of web content from expert perspectives". Infocommunications Journal **(Impact Factor: 1.16)**, **(Accepted).**

[A13] Jinat Ara and Cecilia Sik-Lanyi, "A Declarative Model for Web Content Accessibility Evaluation Process", In International Conference on Computers Helping People with Special Needs, ICCHP 2024. Lecture Notes in Computer Science, vol-14750, pp.84-92. Springer, Cham. https://doi.org/10.1007/978-3-031-62846-7_10

[A14] Jinat Ara, and Cecilia Sik-Lanyi, "Automated evaluation of accessibility issues of webpage content: Tool and Evaluation", Scientific Reports, Springer, 2025; 15(1), pp. 9516. DOI: https://doi.org/10.1038/s41598-025-92192-5, **(Impact Factor: 3.8)**.

[A15] Jinat Ara, and Cecilia Sik-Lanyi, "A Comparative Study: Effectiveness, Reliability, Acceptability, and Fairness of Automatic Web Accessibility Evaluation Tools", Journal on Multimodal User Interface, Springer, **(Impact Factor: 2.2)**, **(Under review).**

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https://m2.mtmt.hu/gui2/?type=authors&mode=browse&sel=10081343

References

[1] World Wide Web Consortium, 2022a: W3C — Web Accessibility Initiative (WAI), Making the Web Accessible. URL: http://www.w3.org/WAI/

[2] Dominic, P. D. D., Jati, H., Sellappan, P., & Nee, G. K. (2011). A comparison of Asian e-government websites quality: using a non-parametric test. *International Journal of Business Information Systems*, *7*(2), pp. 220-246.

[3] Pinto, A., Köpcke, L. S., David, R., & Kuper, H. (2021). A National Accessibility Audit of Primary Health Care Facilities in Brazil—Are People with Disabilities Being Denied Their Right to Health? *International journal of environmental research and public health*, *18*(6), 2953.

[4] World Wide Web Consortium, 2022b: About w3C, Groups. URL: https://www.w3.org/Consortium/activities

[5] World Wide Web Consortium, 2022c. Web content accessibility guidelines (WCAG). URL: https://www.w3.org/standards/

[6] World Wide Web Consortium, 2018. Web content accessibility guidelines (WCAG) 2.1. URL: https://www.w3.org/TR/WCAG21/

[7] Ellis, R. D. Website usability and content accessibility of the top USA universities.

[8] Ismail, A., & Kuppusamy, K. S. (2019). Web accessibility investigation and identification of major issues of higher education websites with statistical measures: A case study of college websites. *Journal of King Saud University-Computer and Information Sciences*.

[9] Rashida, M., Islam, K., Kayes, A. S. M., Hammoudeh, M., Arefin, M. S., & Habib, M. A. (2021). Towards developing a framework to analyze the qualities of the university websites. *Computers*, *10 (5), 57.*

[10] Hackett, S., Parmanto, B., & Zeng, X. (2005). A retrospective look at website accessibility over time. *Behaviour & Information Technology*, *24*(6), pp. 407-417.

[11] Ringlaben, R., Bray, M., & Packard, A. (2014). Accessibility of American university special education departments' web sites. *Universal Access in the Information Society*, *13*(2), pp. 249-254.

[12] Kuppusamy, K.S.; Balaji, V. Evaluating web accessibility of educational institutions websites using a variable magnitude approach. Univers. Access Inf. Soc. **2021**, 1–10.

[13] Ara, J., & Sik-Lanyi, C. (2023, May). AccGuideLiner: Towards a Modelling Approach of Web Accessibility Requirements following WCAG 2.2. In 2023 IEEE International Conference on Smart Information Systems and Technologies (SIST) (pp. 10-15). IEEE.