C-ABLE - Preparing the submarine cable industry to the S-100 standard

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ABSTRACT

The International Hydrographic Organization requires the members of the International Cable Protection Committee to adhere to the recently developed S-100 standard by 2030. However, the stakeholders face several challenges in the transition from the previous S-57 standard. This study proposes a system that provides a solution to convert files in the previously used formats to a new format that complies with the new standard, as well as a visualization, storage and cable management system. The results of the study can help accelerate the compliance efforts and improve collaboration and coordination within the industry.

KEYWORDS

C-ABLE, S-100 transition, submarine cable

1 INTRODUCTION

Recently, Swedish authorities seized a ship because it was suspected that it damaged an underwater data cable running under the Baltic Sea to Latvia [16]. It is unclear whether there was malicious intent or whether the damage occurred by accident. This accident is one of many examples of damaged network or data cables, which indicates that there is a lack of information on the exact location of these cables.

This lack of precise location data resulted in the release of a new standard, the S-100 standard. The S-100 framework of the International Hydrographic Organization (IHO) aims to standardize and improve the exchange of hydrographic and maritime information [5]. The IHO requires all stakeholders to comply with the S-100 standard by 2030. However, despite its potential to improve situational awareness at sea, several challenges remain in its implementation. First, interoperability and compatibility pose significant obstacles, as many existing maritime systems still rely on older standards such as S-57, requiring costly upgrades and conversions. Second, the complexity of data and structure within S-100, with multiple data product specifications, increases processing demands and potential inconsistencies. Third, implementation costs and technical requirements present financial and logistical barriers, particularly for organizations with limited resources. Fourth, the transition to S-100 introduces the challenge of real-time updates and data quality, demanding reliable data processing, integrity, and security. Finally, international cooperation and standardization remain critical, as different nations may adopt S-100 at varying speeds, leading to discrepancies in maritime data.

Many challenges could be very different for each stakeholder. For example, some stakeholders will need a lot of investments in new technical requirements, where other stakeholders already got the newest software and hardware. Therefore, this report focuses on how to convert the older format to the S-100 standard, how to analyze maritime data and how to efficiently manage cable data.

Since the transition process is in its early stages, the research gap lies within these challenges: **How can submarine cable data be transformed into an S-100 compliant standard, and how can the data accurately be visualized?**

2 RELATED WORK

Modernizing maritime data exchange and visualization requires extensive research because of its complex nature. A significant amount of research examines both the S-100 standard's migration concepts from S-57 legacy systems and industrial developments toward complete interoperable data security systems.

2.1 Interoperability, Standardization, and S-100 Requirements

According to Smith et al. [19] research shows all the technical obstacles and organizational barriers related to S-100 standard adoption. Legacy systems handicap interoperability because they contain inconsistent data formats that lead to high conversion expenses according to the article. The authors in Thompson et al. [21] developed an implementation path that shows the exact specifications of S-100 standards while pinpointing crucial dates for its implementation deployment. Muller and Singh [15] studied the historical development of S-57 to S-100 documenting the responsible technological advancements and progressively complex data structures. These works demonstrate the essential requirement for an integrated conversion and visualization pipeline and our system specifically provides a solution to this need.

2.2 Data Conversion and Integration Techniques

Jones and Patel [9] propose a framework for evaluating data conversion pipelines in maritime systems, emphasizing the challenges of handling heterogeneous data sources. The study supports two-phase processing which combines automated data extraction for structured files but requires manual correction for XLSX formats. According to Williams et al. [22] participants rated structured and unstructured data conversion approaches in maritime systems through a survey providing evidence of the requirement for our proposed combined methodology. The techniques which Martinez and Lee [13, 14] present to handle mixed data structures provide essential information regarding error management and data quality control methods that directly benefit our conversion work.

2.3 User-Centered Design for Maritime Visualization

Lee et al [13] review user-oriented design principles for maritime information systems by highlighting how information screens overfill users and interfaces lack customization for appropriate use. The research by both authors confirms our development of a multi-layered visualization interface that meets the requirements of advanced and non-expert users. The interface design recommendations from Garcia and Roberts [7] influence our layout because they analyze usability challenges for maritime GIS applications from a human factors perspective. The best practices presented by Nguyen et al. [17] regarding maritime visualization tool design support our selection of using overview maps with detailed cable management screens.

2.4 Digital Transformation, Infrastructure Resilience, and Security

The article by Garcia and Nguyen [8] examines the economic and security aspects of digital transformation in maritime infrastructure systems. The research demonstrates that data system updates represent a dual requirement of strategic risk management alongside technological enhancement. Patel and Wu [18] present an analysis of maritime digital infrastructure challenges while sharing vital security information for establishing resilient platform systems. Kim and Larson [11]demonstrate through maritime examples how to construct resilient digital systems by showing how proactive security measures should be implemented. Multiple research experiments demonstrate the critical nature of our system because it deals with data conversion while visual communication and industry-standard security measures for enhanced operational reliability; By integrating these contributions, our work seeks to bridge the gap between legacy maritime data formats and the emerging S-100 standard, thereby supporting both technical interoperability and broader strategic objectives in digital transformation.

3 MATERIAL AND METHODS

The research followed a prototype based approach, which takes the prototype as an embodiment of the research and the solution to the problem described by the stakeholders. It is then validated by user testing, that confirms if the prototype indeed can resolve the challenges without introducing new ones.
The requirements of the system was gathered by understanding the S-100 standard itself, and through interviews with the stakeholder for understanding their specific needs and current practices.

3.1 Processed Data

The system does not rely on much data to operate, apart from the input files that the converter takes, therefore there were no need for data cleaning and processing, just understanding how the data is provided and how can it be transformed. Based on the interviews with the stakeholder, there are two mainly used formats currently used: a .kml/.kmz structured file, and an .xlsx workbook file, which is not always structured the same way. Therefore, the system can transform the .kml/.kmz files automatically, but the .xlsx files require the manual insertion of data-points due to the lack of consistency.
The only data the system loads without any user interaction or uploaded files, is the information about the territories. In the prototype, only the Exclusive Economic Zones are displayed, but in a later phase more specific territories or zones can be added.

3.1.1 kml/kmz files. One of the ways that a user can start creating a cable is by uploading a .kml/.kmz file. This is a file format that was created as a standard for geospatial information, and is supported by many geographic information systems, most notably and originally by Google Maps. A kmz file is a zipped variant of a kml file. The file is structured as an Extensible Markup Language (XML), allowing for wide customization. While this customization is useful for the graphic representation on world maps, the inherent cable information that is stored, very much depends on the way that the file was created. While developing the new system, the way to parse kml/kmz files was generalized, and consistent patterns were found in the data. These patterns were found in <Placemark> and <LineString> tags, that is detailed in section 3.2.1 of this report.

3.1.2 Zone data. The Exclusive Economic Zone data is available on the internet in different formats and details, so for the prototype a github repository [4] was chosen, which stores the zones as polygons, with details of the country it belongs to, from which the countries 3 letter ISO code was extracted and displayed where necessary. There are several other types of zones that would be of interest for the stakeholders, but since these require additional validation on the data level, a decision was made to not include them in this phase of prototyping.

3.2 Prototype

A prototype of a web-based solution was developed as an answer to the challenges posed by the transition to the S-100 standard. During the prototyping process the double diamond design approach was used, which is a useful design tool that helps determining the most vital elements of a proposed system to help identifying the focus points, and its relevance is ensured by its adaptability [12]. This design methodology helps in all phases of designing a prototype, in discovering ideas, defining the requirements, ideating the solutions and finally validating it. The validation is done by user tests and interviews, where vital insights are gained on the system's usability and ability to satisfy the user's needs.
The prototype was developed for the dimensions of computer screens, as the users of these applications would not use mobile devices for the purposes of this application.

3.2.1 Converter. The converter has its own page in the system, and operates as the following figure 1 describes:

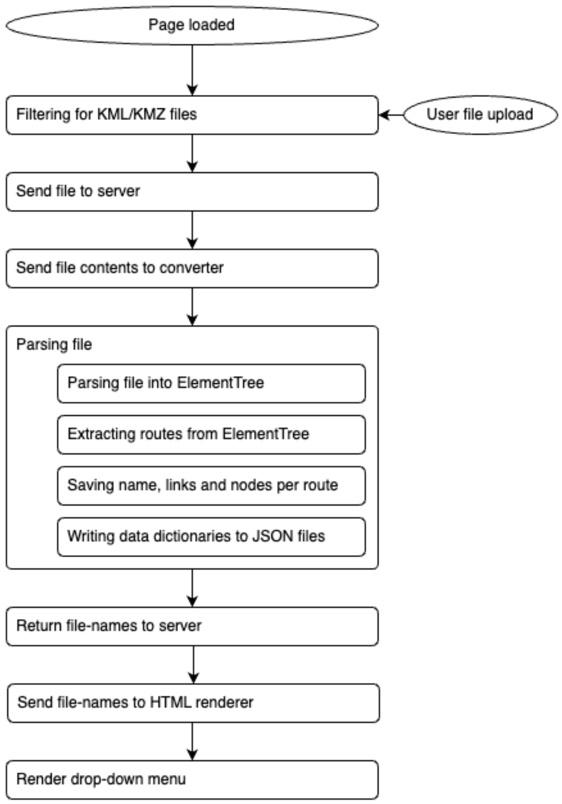

Figure 1: The logical structure of the code of the converter page

The workflow of the converter page starts with the user uploading a file, which can only be in kml or kmz format. The files are stored in a folder, and the filenames are sent to the server through a POST request. The server, in turn, forwards this to the main Python function, which handles the parsing.

The Python code reads the file input, and using an XML-centered library creates a tree structure called an "ElementTree". This is done to easily navigate the data elements. A kml file may contain many different markup elements, and those can be found at any depth of the hierarchy. This is why it was needed to work backwards, and search towards the root of the document. If a document can be seen as a tree structure, then the leaves are containing the nodes and links. These can be detected by finding the outmost sections that fall under the <Placemark> tag. These are then further separated based on whether or not they contain a <LineString> tag. If they do, they are classified as a cable, otherwise they represent a node. Each cable contains coordinate lists, which allows to build up lists of nodes and the links between them. Using the earlier node tags, a check is done to try finding a node's name. If none found in the input file, a unique name is created using an index. When all the cable information is collected into a dictionary, this is written to an output file, and a list of generated output files is returned back to the server.

When the server receives the file names of the generated JSON files, a new section of the converter page is rendered, allowing the user to choose a cable, display it and edit properties of it. Once the user has saved all required changes, they can use the on-page navigation to switch to the overview page, and to continue working on the cables using the map based visualization.

3.2.2 Overview. The cable visualizer is located on the overview page of the web application, and it aims to provide an overview of the cables that are stored in the system. It allows the users to see what segments the cables are built of, information about these segments such as their exact starting and ending points, length, depth and cable type. The main part of the page relies on the Leaflet, which is a lightweight open-source JavaScript library, that handles the geographical data visualization.
The code follows the high-level structure shown in figure 2:

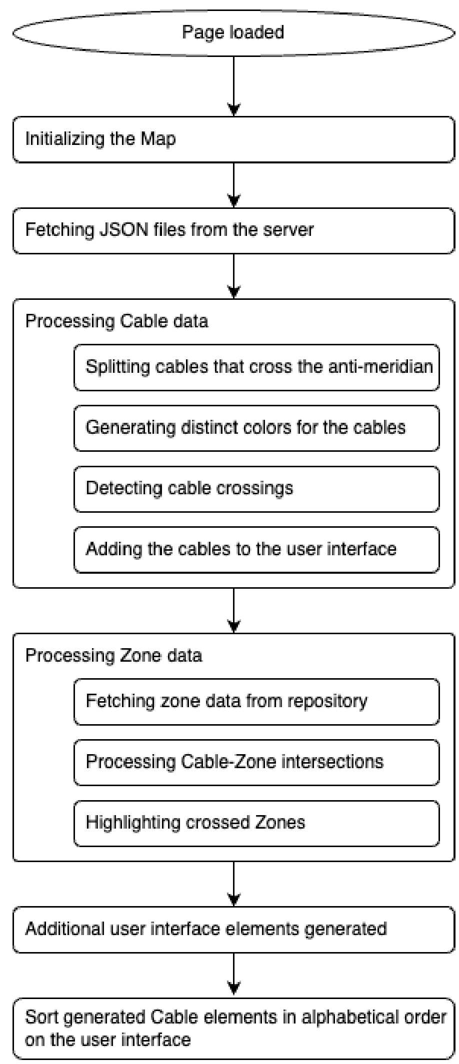

Figure 2: The logical structure of the code of the Overview page

After the map and the JSON files are loaded, the system first checks if there are any cables that are crossing the anti-meridian (de edge of the two dimensional map), calculates the exact location, and splits the cable in two parts to display them on the map. Then a color is generated for the cables, that is ensured to be different from the already existing cable colors, and detects how do the submarine cables intersect each other, and where the exact crossing point is. After that, the exclusive economic zones (EEZs) are loaded and calculated where the cables enter or leave an EEZ. These calculations are done by leveraging the Turf.js library, which can do advanced geospatial analysis in the front-end of web-browsers.
After the calculations are done, additional user interface elements are generated, for example buttons that interact with the cables created. AS a last step, the Cable elements are sorted in alphabetical order to allow the users to find them easily even if the list is quite extensive.

3.2.3 Manage cables. The cable management page allows the users to modify their already uploaded cables, and download or remove them from the system. It operates simply by a combination of JavaScript, HTML and CSS, and communicates with the python based Flask server that hosts the file system via HTTP requests.

3.3 Architecture

The architecture of the application consists of a back-end that is running on a python based Flask [6] server that is also responsible for the file conversion from the kml/kmz files to the S-100 JSON files. Both the original and the converted files are stored in the file system of the server, which the front-end can access and load for visualization and modification.
Two parts of the front-end have access to the files stored in the system, which are the Overview and the Manage Cables part.
The Manage Cable page has both read and write access to the file storage, as on this page users can upload, modify or create cables, as well as remove them and see their details. This part of the prototype only uses CSS, HTML and JavaScript creates HTTP requests towards the back-end.
The Overview page utilizes different libraries for visualizing and computing with spatial data. The visualization relies on the map functionality of the Leaflet library [2], which displays the world map, the cables and the different zones. The prototype visualizes only the exclusive economic zones, that represent all of the national jurisdictions over the sea. The data is loaded from a repository called ReverseGeo [4], that provides the information about any coordinate pair if they are located within a certain countries territory that includes their national sea territory. The Turf.js library [1] is used for calculating if there are any crossing points between any of the cables, or any of the zones. This library is necessary to perform the complex geometric calculations between the polygons and polylines. For the user interface, regular CSS, HTML and JavaScript codes are responsible.

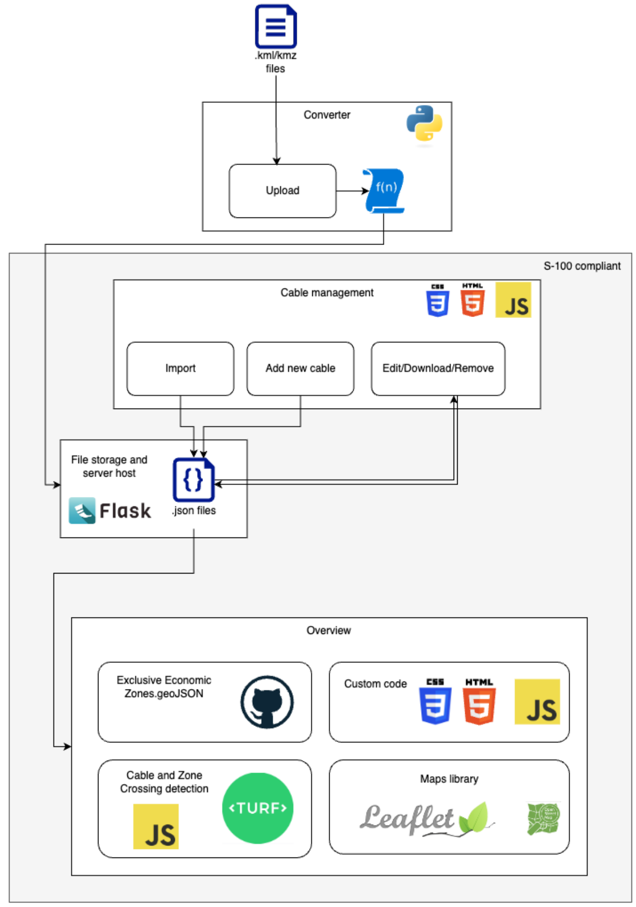

Figure 3: Architectural graph of the main components

3.4 User tests

The user interface was tested by people who were unfamiliar with it but had previous understanding of the project. The tests used the "Think-Aloud" approach and users were asked to complete three tasks, where time and errors were tracked. After completion of all tasks, users were asked to rate ten statements on the System Usability Scale (SUS) [20] from 1 to 5, where 1 represents "strongly disagree" and 5 represents "strongly agree". The statements focused on the user experience. For example, one statement was "I found the system unnecessarily complex". The SUS score is calculated in a way that their polarity are corrected: the results of the negative toned questions are subtracted from 5, and 1 is subtracted from the results of the positive toned questions. The new values are multiplied by 2.5 and summed, and that shows the score out of 100. The average usability score is 68, and if a system receives a better result than 80.3, it is considered a well built system, as users find it easy to use, and would recommend the use of it.

3.5 Team Management

The work was shared between the four authors, and recurring meetings were scheduled for discussing the individual results. The project was divided, so Peter and Ágoston were working on the prototype, while Luc provided the additional research, and Andrei created the script for the user tests.

4 RESULTS

The developed prototype is available in the GitHub repository [3]. The converter and the overview page of the system provides a clear solution to the stakeholders' challenges. The first challenge is answered by the standardized, new JSON file format, that stores all the necessary information, while being structured in a way that web-applications can handle them with ease. The overview page aims to resolve the other main challenge by accurately visualizing the data and the relations between the different elements.

4.1 Structured data

There are a few requirements for the format of the data for storing the cables. The format needs to be hierarchical, in order to be able to navigate both horizontally from node to node, but also vertically from a node to its coordinates and to the depth of the end coordinate, for example. It is a requirement to have a way to add information in a way that scales well, in order to expand upon the fields that are currently of interest, using fields that must be added later. Lastly, since many different users are interacting with the files, it needs to be both humanly legible and easily interpretable/displayable by a computer system. Fairly quickly JavaScript Object Notation (JSON) has been chosen, and during both research and development this proved to be a good decision. Due to these attributes of the format, it was easy to communicate about the structure of the format, and because allowed parallel development of the system, before accessing the future keys.
The hierarchical structure of the generated JSON files are shown on figure 4. The ellipses represent how the information stored in the format can be extended.

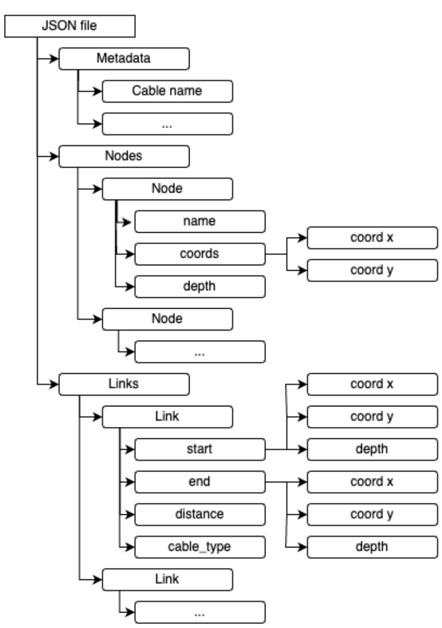

Figure 4: The structure of the generated JSON files

One of the main advantages of this structure is that as long as the above described elements are in place, any other information can be added that other system may use or require, it does not affect the proposed system's usability.

4.2 User Interface

The user interface consists of the five web-pages of the platform, which are all available at any point from the main navigation element. The Home page acts as a landing page, and also provides navigation. The About page provides an bit of insight into the challenge of the S-100 format transition and describes the three main workflows. The Converter page contains the conversion tool, the Overview page visualizes all the cables stored in the system, wile the Manage Cables page allows users to commit administrative changes or modify the cables data.

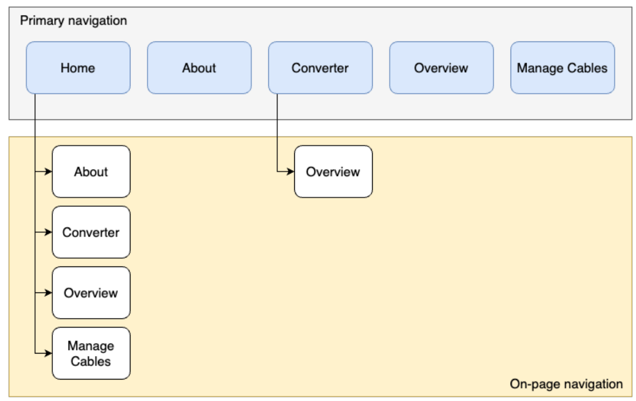

Figure 5: Navigation elements

4.2.1 *Converter User Flow.*

The user flow of the converter page is described in figure 6. The users can convert files in the old kml/kmz format to the new JSON based format following these steps. In this workflow users also have an option to modify the cables, if any problem occurs during the conversion, or if any of the original datapoints were incorrect.

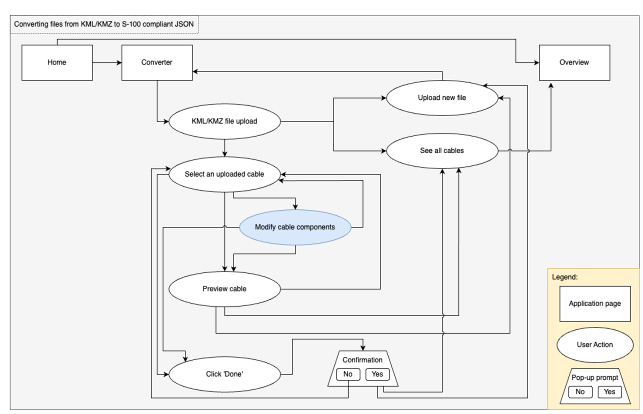

Figure 6: Converter User Flow

4.2.2 Manage Cables User Flows. There are several possible user flows that can be associated with the page, which are importing, creating, downloading, removing and modifying a cable in the S-100 standard compliant JSON file. These are shown in detail on figure 7 below.
The page itself consists of four segments, one for each function. This way all of the possible workflows are visible to the user when the page has loaded, and they can perform any of them.

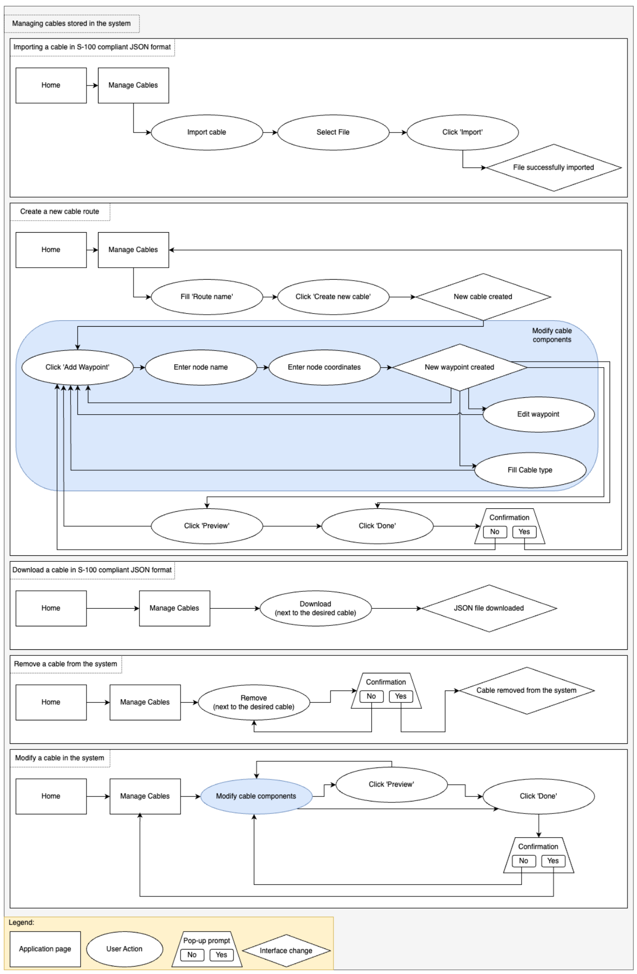

Figure 7: Manage Cables User Flows

4.2.3 Overview User Flows. The users can execute actions such as zooming in on the crossing points and hide or show certain elements of the map.
The main user flow of the page is detailed on figure 8 below, but in summary, users can select a cable that zooms-in on the cable on the map, and also shows the details of the cable in the control panel: the segments that the cable consists of, their precise location; the filtered intersection points with both the other cables and the zones, with their exact location. To avoid the map to be too cramped, the users can hide or show all and specific cables.

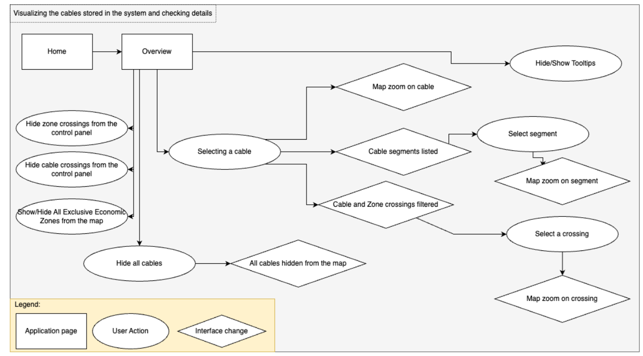

Figure 8: Overview User Flow

4.2.4 User Interface Validation. The SUS tests resulted an average score of 82.5, indicating that the interface is user-friendly, and people love the site and would recommend it. However, the test-subjects made comments during the test, implying that the site could be improved. For instance, the test subjects were not sure if the file was already converted after uploading, or they needed to perform additional actions.
Overall a common comment was regarding naming convention, as they did not find everything consistent, not just within the system, but also with the lingo of the industry.

5 DISCUSSION

Initially there were two parts of the application in development, as the stakeholder requirements included the converter tool and the visualizer tool, and the third part became a clear necessity after these two: an administrative interface was required to manage the information stored in the system.
While designing the user interface, two important principles were kept in mind: First of all, providing easy access to all the necessary functionalities for the advanced users, while also keeping the interface simple enough, that users without any prior knowledge of the system, are able to navigate the platform with ease. Secondly, adhering to the S-100 standard by showing every detail of the cables that is required by the IHO and ICPC.
The user tests have confirmed that most of the design decisions were correct, as using the prototype did not require prior learning of the platform. Since the users had different levels of knowledge about the submarine cable industry, a comparison was possible to see how that affects the usability. As the results show, the first principle was a success as users with different backgrounds could use the application effectively.
The success of the second principle is harder to quantify, as in some cases the S-100 standard is very broad in what is required on the technical level, but the main point of compliance lies within the generated file format. The standard mentions some file formats, but as there are no best practices in the industry yet, it needs further research in determining which one would be the best fit for all the needs. Therefore, since the main requirement is to have a hierarchical file structure, the decision was made to create a JSON file, that is hierarchically organizing the data, and it is easy to transform to other file formats, if at a later stage it will be necessary. That is the

main reason why not a more specific format - such as GeoJSON - was chosen; to keep the new file in a format that any system can easily handle.
The workflows were designed in a way that the users do not have to keep many steps in mind, and due to the modular approach, they do not need to skip certain steps of a unified process, but they can commit the very action they need. The user tests have also proven this, as the subjects of the tests were able to quickly find how they can perform the workflows.
In reflection to the comments received during the user tests, the prototype needs to be improved in certain areas, such as naming conventions, and the usage of 'routes' instead of 'cables' avoided.
Some challenges emerged during the development of the prototype, which were mainly related to the calculations of the intersections of the different geometrical elements, which required continuous development of the method. Another challenge was introduced with some test cases, where a cable crosses the anti-meridian line, which initially caused the visualizer to draw unwanted lines on the map. This was resolved by introducing a function that runs in the front-end - therefore it is not modifying the stored data - and after computing the exact coordinate where it crosses the edge of the map, it splits the cable there and visualizes them as two separate cables on either side of the map.

6 CONCLUSION

This prototype based study describes a possible solution for the question: How can submarine cable data be transformed into an S-100 compliant standard, and how can the data accurately be visualized?
The first part of the question is answered by the proposed JSON based file structure and converter, while the overview page reflects on the second part. The study highlights the minimum requirements of what elements such a system needs to contain in order to adhere to the S-100 standard. However one system will not resolve the submarine cable industry and its stakeholders face, it requires a more technically concise standard that requires all the companies to use the same file formats.
In order to provide a comprehensive solution for the challenges the cable owning, installing and maintaining companies and governing bodies are facing there are some aspects that needs to be improved, that are described in the following section.

6.1 Future Work

In order to completely satisfy the stakeholder expectations and requirements, the system needs a few more features that this prototype does not include due to the limitation of the scope.

6.1.1 Security. As the system stores business critical data, it needs to ensure that the information stored within is secures, unauthorized access is blocked and the users' actions are logged on an appropriate level.

6.1.2 Profiles. Related to the security of the system, but more specifically, user profiles with different access are required, so they can be mapped to the proper administrative roles.

6.1.3 Communication. A current challenge of the submarine cable industry is that there is no official tool for communication about the cables. As a future possibility the system could be able to integrate communication between the companies, by sharing the minimum required information about their own cables, and follow the changes that happen during the deployment of a cable.

6.1.4 Scalability. The current prototype runs on a locally hosted server, but if it was to be deployed for a wider audience, not just the infrastructure, but the code needs to be modified as well. Currently the processing of the cable and zone crossings are done by the user's browser, in the front-end, which in case of an increased number of cables, can strain the user's machine.

6.1.5 User interface. Even though the usability score of the prototype is quite high, improvements can be done on the interfaces to make it even more simpler to use and also implement the other features mentioned in the future works section.

6.1.6 Ethical considerations. While the cables laying in the seabed do not harm the environment as Jurdana et. al [10] concluded, however, their deployment and maintenance can be highly polluting. As this was not taken into consideration in the current prototype, in future iterations, it would be important to at least highlight the territories that require more protection. This way the stakeholders could account for that during the planning phase of the cable deployment and minimize their local ecological footprint in those areas.

7 CRITICAL REFLECTION ON THE USE OF AI

In the early phases of prototyping generative AI (ChatGPT) helped with generating different test files that allowed testing in edge cases, such as cables crossing the anti-meridian, and also the robustness of the system and the capacity to handle multiple cables simultaneously. As there were limited real cable data available, this was very useful to avoid to create dummy data manually. These did not need validation, as their accuracy did not matter for the prototype. An empty file with the structure was uploaded, and with prompts such as "generate a similar file, where the coordinates draw a line that connects two seaside cities on water" was used to generate these files.
Additionally, generative AI was used to aid the creation and work on one of the JavaScript files. This file handles the HTML manipulation while editing cables in the browser. Since code like this was found to be very specific in existing sources, the choice to use GenAI helped to increase the speed of development in this section. Working with it involved a lot of fine-tuning, and even though often the generally correct code was generated, often additional attributes had to be added, that either were not requested or were not compatible with other parts and files of the system. For this reason a lot of care and assistance was required to make sure the code only included the correct lines.

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