Design of user interface for sewer management web application

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The fast-increasing amount and complexity of data in sewer management exert pressure on outdated client-side software programs, leading to operational difficulties and user complaints. This highlights the urgent need for a user-friendly web-based sewer management application capable of effectively managing complex data, whose research has been overlooked. Hence, to bridge the gap, this research endeavors to develop a user interface for sewer management web application incorporating web design principles and data visualization techniques to ensure optimized usefulness, usability, aesthetics, interactivity, and ease of use. The five-step model of Design Thinking Process from Stanford was followed throughout the whole design process. The literature review and the interviews with domain experts were conducted to understand user needs, based on which the interactive design was developed. A modified technology acceptance model, containing 7-point Likert-Scaled questions, was adopted to evaluate the final design with five domain experts. The evaluation result shows that the majority of participant responses for perceived usefulness and aesthetics are in the range of 5 to 6, 4 to 6 for perceived usability and interactivity, and 4 to 5 for perceived ease of use, indicating that the design effectively addresses the major challenges identified in current software solutions and therefore contributes to bridging the research gap.

Additional Key Words and Phrases: Sewer management, User interface design, Data visualization, Usability, Aesthetics, Interactivity

1 INTRODUCTION

The importance of Sewer Asset Management (SAM) has been strengthened in recent years due to economic considerations [2]. The decision-making process in SAM has an ongoing and massive impact on the performance of sewer assets. One of the key factors that support the decision-making process is *Predictive Maintenance* (PdM) [2, 19]. PdM is a maintenance approach that utilizes tools such as artificial intelligence, machine learning, and deep learning to predict possible failures before they occur [18]. PdM has gained significant attention in research in asset management [19]. However, there are multiple challenges in the successful implementation of the PdM approach. One of the biggest challenges is the high quality of human management and skill [18]. Another key challenge is data management [1]. The amount of data is growing fast in SAM, and the data types are becoming more complex, which makes it more challenging for asset data management [2].

Based on the interview with domain experts, we found out that the majority of the software used today for sewer management is a client-sided program, which must be manually installed on the client side, therefore precluding shared data access among users. Different versions of programs are used by users simultaneously, which makes it difficult for them to manage user complaints. Moreover, the interface is outdated and not comparable with visually pleasing web interfaces. Therefore, the development of a web program for sewer management that better supports centralized processing, version control, shared data access, and usability is urgently needed.

To tackle these challenges, a web User Interface (UI) that incorporates suitable and visually pleasing visualization and interpretation of data used for PdM and enables asset managers with easy-to-use data manipulation and analysis tools is essential.

However, while there has been extensive research on applying web design principles in distinct areas, such as healthcare, education, and business, the field of sewer management has been largely overlooked. Therefore, to bridge this gap, this research developed a UI for sewer management web application incorporating web design principles and data visualization techniques, such as, *data processing*, *chart selection*, *color choice*, and *interactivity design*.

The UI design includes four modules, namely, *GIS*, *Prognostics*, *Maintenance Policy Optimization* (MPO), and *Statistics*. Although *usability* is essential in the design and development of user interfaces, it is no longer a dominant factor of user satisfaction because *aesthetics* is becoming more influential in UI design [24]. Another key concept in UI design is *interactivity* [25].

A modified *Technology acceptance model* (TAM) that integrates metrics such as usability, aesthetics, and interactivity, in addition to perceived usefulness and ease of use, is used for the UI evaluation.

2 RESEARCH QUESTIONS

We frame our research with the following questions:
RQ1: What are the design principles to incorporate in web UI design for sewer management web application?
RQ2: What are essential elements to include in the UI of sewer management web application?
RQ3: How does the UI design perform regarding perceived usefulness, ease of use, usability, aesthetics, and interactivity of the modified Technology Acceptance Model (TAM)?

3 RELATED WORK

In order to gather related literature, databases such as Web of Science, IEEE, Scopus, and Google Scholar are used. Search terms such as "web usability principles," "user interface design," "data visualization," "sewer infrastructure management," "sewer management," and "sewer asset management" are used.

3.1 Sewer Asset Management: Domain-Specific Needs, Requirements and Challenges

3.1.1 Asset Management.

Asset management is an approach that utilizes economic, management, engineering, and other practices to manage assets to prolong asset life expectancy, enhance asset performance, and minimize cost [4]. The management goals are to ensure stable and reliable sewage treatment, optimize and extend the life of the infrastructure, reduce

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maintenance costs while complying with laws and regulations, and meet user needs. The goals also seek to identify and manage risks related to infrastructure failure, and improve decision-making capabilities and levels [4].

The biggest challenge in sewer management is to achieve sustainable management [4]. There are many definitions of the concept of *sustainability*. Berndtsson et al. (2008) [5] believe sustainability lies in achieving ecological sustainability. Han et al. (2015) [6] believe that this sustainability not only requires reducing maintenance costs but also improving user satisfaction. Marlow et al. (2010) [4] argue that integrating ecology, environment, and hydrology is the key to sustainability. Although different scholars may have distinct interpretations of sustainability from different standpoints, they agree that the ultimate goal of sewer management is to achieve sustainable management.

3.1.2 Data Management.

Okwori et al. (2021) [1] think that effective *Data Management* is essential for decision-making in SAM. They also conclude that effective data management can lead to more accurate life expectancy prediction for sewer infrastructure, which is critical for optimizing maintenance policy-making and improving the sustainability of SAM.

In actual practice, the storage and management of data are usually carried out in different ways [3]. There is no established channel between them for data to flow dynamically, which imposes great challenges to the management and analysis of data [3]. The features of centralized data processing in web applications and visualized data presentation in web user interfaces will bring considerable improvements to data accessibility and usability.

3.1.3 Geographic Information Systems integration (GIS).

Compared to traditional data management practices, GIS brings great advantages in establishing networks of infrastructure, data extraction, data analysis, visualization, and the visualized display of analysis results [28]. Halfawy et al. (2005) [29] have shown the importance of GIS integration in their research. The effectiveness of a poorly integrated GIS will be greatly reduced. This is because functionalities of GIS usually need to be customized for specific needs. If there are no matched functionalities, the effectiveness of GIS maybe even less than that of traditional management methods. Therefore, the integration of GIS systems is particularly important.

3.1.4 Prognostics and Maintenance Policy Optimization (MPO).

PdM is a recently brought-up maintenance approach that aims to improve asset performance, prolong asset lifespan, and achieve cost-effectiveness by predicting asset failures before they occur using prediction models [18].

MPO is a process to optimize responses to predictive alerts. In the context of sewer management, MPO refers to balancing the pros and cons of multiple system variables to achieve the maximization of facility life or performance, cost minimization, or system failure risk minimization [3].

Therefore, considering the promising benefits PdM and MPO could bring to sewer management, it is important to integrate them into the sewer management UI and present complex predictive data and MPO data in an intuitive, easy-to-understand manner to enhance their usefulness.

3.2 User-Centered Design Principles and Best Practices in Web User Interface Design

3.2.1 Data Visualization.

Data visualization is a process where data is converted from textual and numerical forms into graphical and image forms [12]. The goal of data visualization is to present data to users in a more beautiful, aesthetically pleasing, easy-to-read, and understandable way [13].

Key aspects include data processing, where complicated data is simplified while original data is made accessible to users [14]. This can be achieved, for example, by using conventionally accepted symbols.

Chart selection is crucial in data visualization, which involves selecting suitable visualization techniques based on the data's nature and user characteristics [13].

Color choice is essential in design. Eye-catching colors can be used to highlight specific elements while fading colors can achieve the effect of de-emphasis [14]. And the selection of colors must consider potential distractions and difficulties for color-blind individuals [15].

Lastly, interactivity plays a vital role in data visualization. Strategies such as selecting, linking, and filtering allow users to manipulate the data representation, establish dynamic relationships, and focus on specific data features [16].

3.2.2 ISO 9241.

ISO 9241 provides ergonomic guidelines for human-computer interaction, with a particular focus on usability, user-centered design, and guidelines for data presentation [7]. Since its introduction, ISO 9241 has been widely applied and cited in various fields of research in academia, confirming its effectiveness in guiding UI design centered on usability. For instance, Farinango et al. (2018) [7] showed that the application of ISO 9241 helped keep the entire design and development process of personal health record system centered on users and user experience, ultimately improving user satisfaction and acceptance.

Although there has been much research on the application of ISO 9241 in specific fields, the research on applying ISO 9241 to the UI design of SAM web applications has been overlooked. Therefore, this research aims to bridge the gap by incorporating web design guidelines from ISO 9241 with requirements and challenges in SAM. Particularly, part 151 [21] of ISO 9241: Guidance on Web UI Design will be followed in the UI design.

4 METHODOLOGY

The methodologies followed during the research process are described in this section. The diagram of the methodology overview can be found in Figure 1.

4.1 Literature Review

Literature review has been done to identify data visualization techniques, web design guidelines, and requirements and challenges in the sewer management field. Further literature review has to be done to gain insights into methodologies to conduct throughout the research process, such as interview techniques, UI evaluation techniques, and internal reliability analysis techniques.

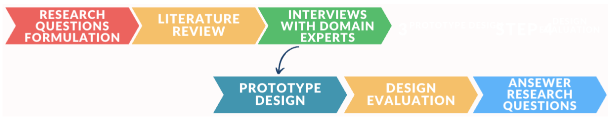

Fig. 1. Diagram of methodology overview

4.2 Design Thinking

Design thinking is an iterative process of analysis and realization that typically includes discovering user needs, defining problems, ideating, prototyping, and testing [8]. Design thinking has been widely applied in many domains due to its effectiveness in IT, business, education, and healthcare [9].

Many models based on the original concept of design thinking have been developed. The most effective models include the HCD and 3I model from IDEO and the five-step model from Stanford [10]. The five-step model is adopted in this research due to its effectiveness, the process of which can be found in Figure 2.

The first stage of this model is to understand user requirements. The second stage involves articulating problems based on the gathered requirements. The third stage contains activities for generating ideas based on identified problems. Building interactive prototypes for produced ideas and evaluating prototypes with end users are the final two steps [10].

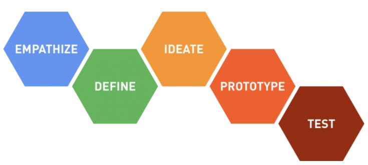

Fig. 2. Five-Step Design Thinking Process Model

4.3 Requirement Elicitation Interviews With Domain Experts

The book by Lazar et al. (2017) [11] sheds light on conducting research interviews in the field of human-computer interaction. This research utilized the methodologies from the book to guide the interviews and approach interview analysis.

The interview stage is a part of the "Empathize" phase of the five-phase model put forth by Stanford's Hasso-Plattner Institute of Design [8]. A pilot interview was conducted with an asset manager before the formal interviews. This interview serves as an opportunity to reflect on the whole interview process, refine and revise interview questions that were irrelevant, unclear, and missing the point. We also aim to modify and improve the structure of interview questions and grasp the pace of the interview more effectively by conducting the pilot interview.

The semi-structured interview technique was adopted in the interview with five domain experts from the field of SAM. This technique was chosen because it offered more flexibility than fully-structured interviews and the opportunities to ask follow-up questions when a deeper understanding of a specific topic is needed. Semi-structured interviews also avoid the lack of consistency compared to unstructured interviews, where there are no planned interview questions.

Based on the literature review that has been done on the requirements and challenges in sewer management, the interview questions were divided into two groups:

1. The objective of the initial category of questions is to discover the key functionalities and features essential to the SAM system from the asset manager's perspective.

2. Uncovering the requirements and expectations for GIS, Prognostics, Maintenance Policy Optimization, and statistics in the web application for managing sewer assets is the goal of the questions from category 2.

The complete compilation of interview questions is provided in Appendix A.

4.4 User Interface Evaluation

Since brought up by Fred Davis in 1989, Technology Acceptance Model (TAM) has become one of the most effective methods for investigating a technology's user acceptance [17].

TAM includes two measurement criteria, namely perceived usefulness, and ease of use [17]. Perceived usefulness refers to what extent users believe that utilizing a specific system will enhance work efficiency, and the concept of perceived ease of use refers to what extent users consider that utilizing a particular system would be devoid of effort or difficulty [17].

While TAM has been proven effective, several studies have presented modifications to address its limitations. For example, Lah et al. (2020) [27] proved the feasibility of constructing perceived usability in TAM. In this research, the TAM is modified to include three more criteria, namely usability, aesthetics, and interactivity, based on the research needs.

4.5 Internal Reliability Analysis: Cronbach's Alpha

From the research of Tavakol et al. (2011) [26], we get to know that since it was introduced by Lee Cronbach in 1951, Cronbach's Alpha has been widely used in many research fields as an effective way to quantify the *internal consistency* of a set of test items or scales. Tavakol et al. (2011) define internal consistency as the degree to which all test items measure the same underlying construct. They indicate that Cronbach's alpha is between the values of 0 and 1, and a higher value indicates better internal consistency, while a lower value suggests inferior internal consistency. Although a generally acknowledged Cronbach's Alpha's value is 0.7, 0.6 is also considered acceptable [22].

5 RESULTS

5.1 Interview Findings

The method used to analyze the interview data is content analysis [11]. This strategy involves analyzing the frequency of words, and it is indicated that words of higher frequencies should get more consideration. The interview findings are categorized based on the interview question categorizations.

5.1.1 Requirements and Needs in Sewer Asset Management.
Drawing from the literature review and the interview analysis, the design can be separated into four modules: GIS, Prognostics, Maintenance Policy Optimization, and Statistics. Domain experts expressed their preferences and expectations for each individual module while stating that certain design consistencies should be followed throughout the entire design, such as adhering to consistent design layouts, providing help guides in each module, integrating different modules more closely, and enhancing interactivity.

The following are the essential functions delineated for each module:

1. Module of GIS: A parameter setting panel to filter on the GIS map based on selected parameters, such as minimal pipeline age, maximal pipeline age, inspection date, damage type, material, remaining life span, etc. Pipeline data visualization and management, including displaying data in charts, graphs, and tables, as well as giving users access to edit, add, remove, and export data.
2. Module of Prognostics: A parameter setting panel to select the desired combination of the damage code, probability model, type of graphs, and the level of analysis. The prognostic plots should be interactive in a way that the prognostic plot outcomes are mirrored on the GIS map.
3. Module of maintenance policy optimization: A parameter setting panel to select prediction models, levels of analysis, and types of plots. Close integration between the plots and the GIS map. The maintenance policies of each pipeline should be accessible.
4. Module of Statistics: Freedom to select various combinations of graph type and data type. Close integration between the statistical graphs and the GIS map.

5.2 Prototype Development

5.2.1 Low Fidelity (Lo-Fi) Prototype.

The Lo-Fi prototype was created based on the literature review and interview findings. This stage is a part of the "Ideate" phase of the five-phase model put forth by Stanford's Hasso-Plattner Institute of Design [8]. The Lo-Fi prototype outlines the initial design's basic functionalities, features, and layout. By iteratively gathering feedback on the Lo-Fi prototype from domain experts and improving the design by incorporating the feedback, a High-Fidelity prototype was developed.

The Lo-Fi prototype is comprised of four modules. All modules have a parameter setting panel. The module of GIS has a comprehensive GIS map and a pipeline data management table, which can be found in Figure 3. The module of Prognostics, the design of which can be found in Figure 4, contains the graphic presentations of state probability predictions over pipeline age, which is critical for asset managers to make maintenance policies. The plots in the MPO module include visualizations of essential information for optimizing maintenance policies, which is shown in Figure 5. The module of Statistics, in Figure 6, shows an overview of important network statistics as well as their visualizations.

5.2.2 High Fidelity (Hi-Fi) Prototype.
This stage is a part of the "Prototype" phase of the five-phase model

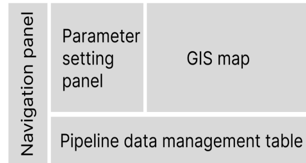

Fig. 3. Module of GIS

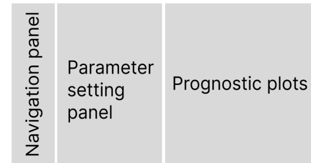

Fig. 4. Module of Prognostics

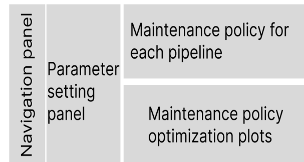

Fig. 5. Module of Maintenance Policy Optimization

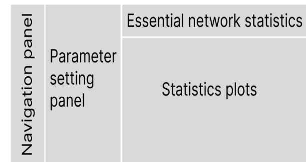

Fig. 6. Module of Statistics

put forth by Stanford's Hasso-Plattner Institute of Design [8].

The navigation, color scheme, and layout designs follow the identified data visualization techniques and the web UI design guideline ISO-9241-151. The navigation, layout style, and color scheme are consistent in the design of every module.

Each module has a navigation panel on the left side to show users where they are and navigate them among different modules. The visual design of the navigation component is consistent. For instance, the expand button, the close button, the information button, the switch button, and the design of the navigation panel are uniformly designed so that users can quickly learn how to use them and rely on them to achieve their goals. The design of the navigation structure makes it clear to users when there are multiple levels in the navigation structure.

To keep the design visually pleasing and the information easy to interpret, a limited number of colors are used in the design. Blue is chosen as the primary color since it indicates integrity and reliability in the Western cultural context. High-contrast colors are used when it is necessary to differentiate from the background color.

The layouts of each module are consistent, with a navigation panel on the left side, a parameter setting panel in the middle, and the main content on the right side, which is intuitive and easy to follow. The designs of layouts within the navigation panel, parameter setting panel, charts, and tables are also consistent, which aims to cut down on the learning cost for users.

5.2.3 Module of GIS.

The GIS module serves as the interface to give an intuitive visual display of the status and conditions of the pipeline network. This module contains three components, the parameter setting panel, the GIS map, and the pipeline data management dashboard. The design of this module can be found in Figure 7.

The search fields within the parameter setting panel allow asset managers to select the prognostic and maintenance policy optimization models and corresponding parameters. The year selection bar enables asset managers to view any specific year's pipeline network, whether from the past, present, or future. This is a useful feature since it allows asset managers to visualize the changes in conditions of the pipeline network with time changing.

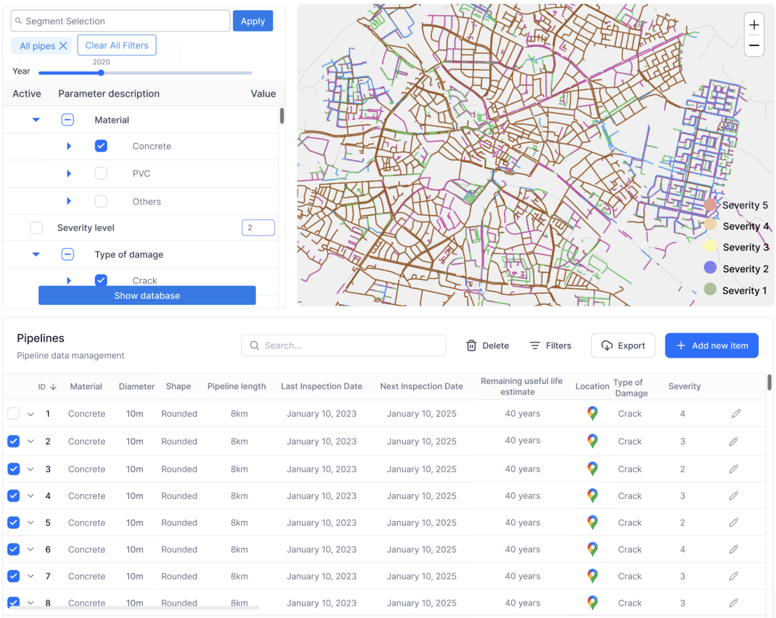

Fig. 7. Module of GIS

The GIS map shows a visualized geographical network of pipelines based on the parameters set from the parameter setting panel. Different colors, representing distinct types of conditions, are marked on pipelines. Green, blue, brown, and red mean minimal, moderate, severe, and catastrophic damage, respectively. The zoom button on the map allows asset managers to view the network from an overall or specific perspective. By clicking on a specific pipeline on the GIS map, a popup box containing detailed information about the pipeline, such as material, shape, remaining lifespan, and a chart showing the type of damage and severity level from various parts of the pipeline over time will show up.

The pipeline data management dashboard presents the pipeline data filtered by the parameters. This dashboard gives detailed information on the pipeline, including ID, material, diameter, shape, content length, last inspection date, condition, remaining useful life estimate, location, type of damage, and severity. By clicking the map icon, users will be directed to where the pipeline is located on the map. When expanded, more detailed information will be shown under each row. Given the options of searching, filtering, deleting, exporting, and adding pipelines, users can better manage the pipeline data.

5.2.4 *Module of Prognostics.*

The objective of the module on prognostics is to enable asset managers to predict potential failure rates, estimate infrastructure lifespans, and visualize prognostic plots. The design of this module can be found in Figure 8.

The parameter setting panel allows the user to select the type of pipelines, damage code, type of model and corresponding parameters, and level of analysis that consists of network level and pipeline level, to model the prediction.

The prognostic plots are represented in graphs with scatter plots, curves of different thicknesses, and confidence bands that give users a visualized overview of the probability of pipelines being in a certain status with pipeline aging and the prediction uncertainties. The graph, which summarizes all of the predictions, is shown to indicate the probability of the pipeline network being at a certain severity level with pipeline network aging. The predictive result is visualized on the GIS map. A GIS map containing pipelines for various conditions of that timeline will pop up by clicking a specific timeline on the combined graph. This feature mirrors the predictive result on a real infrastructure network, which is valuable for informed decision-making and planning.

5.2.5 *Module of Maintenance Policy Optimization.*

This module provides essential information for optimizing maintenance policies in decision-making. The design of this module can be found in Figure 9.

On the left portion of Figure 9 is the parameter setting panel, which allows users to select types of pipelines, models, plots, and levels of analysis.

On the top right side of Figure 9 is the maintenance policy table, displaying the actions needed for each pipeline over different periods under various policies. Users are also given the capability to manipulate the data.

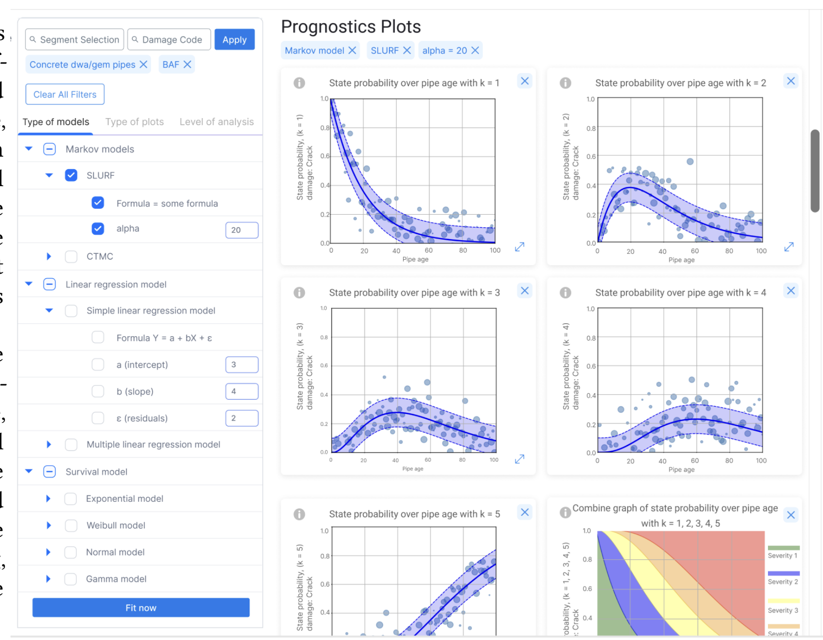

Fig. 8. Module of Prognostics

On the bottom right side of Figure 9 shows the plots, which include repaired pipeline length over time, overall maintenance cost over time, number of pipelines for each action over time, pipeline or network reliability over time, maintenance cost over policy, and pipeline or network reliability over policy. Based on their characteristics, the graphs are represented in different forms, such as curve charts, bar charts, and line charts. The charts are also interactive. By clicking on different components, pop-up boxes, including information on how to interpret the charts, will be shown.

With this information visualized, it is beneficial for users to analyze the reliability and maintenance costs of various policies to find an optimal balance between reliability and cost.

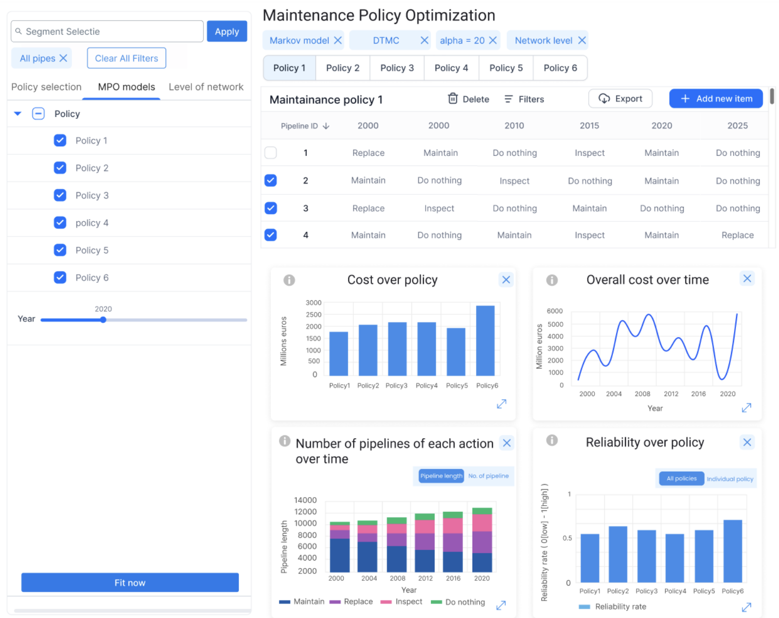

Fig. 9. Module of Maintenance Policy Optimization

5.2.6 *Module of Statistics.*

This module aims to provide users with various statistics of the pipeline network to facilitate decision-making. Users can select the combination of city, chart type, and data type on the parameter setting panel to generate the statistics plots. Refer to Figure 10 for the design.

The network information is outlined using key performance metrics such as total inspections, pipeline length, pipeline count, and construction time. When users click on the specific information area, histograms with more detailed information will be shown. For example, the total number of pipelines histogram shows the number of pipelines from the year 2000 to 2020 and the proportions of pipelines in various severity levels.

The charts show essential statistics on pipeline network materials, shapes, content, functions, remaining life span, status, and width. The statistics are visualized by allowing users to click on different components on charts. For instance, by clicking on concrete from the pie chart of materials, a GIS map with pipelines made of concrete will pop up.

5.3 User Interface Evaluation

This stage is a part of the "Test" phase of the five-phase model put forth by Stanford's Hasso-Plattner Institute of Design [8]. The evaluation was conducted with five domain experts. The procedure for

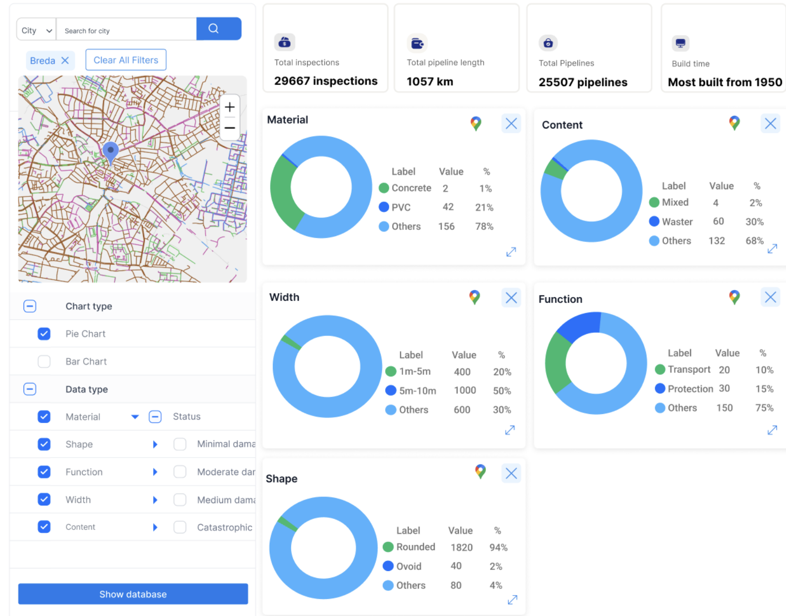

Fig. 10. Module of Statistics

all participants is as follows:

1. Browse the design with the main features and functionalities.
2. Watch the recordings of the simulated UI interaction.
3. Answer the questionnaire questions.

A questionnaire was created based on the modified TAM to evaluate the UI. The questionnaire was separated into four parts, corresponding to the four modules, each of which was validated for its perceived usefulness, ease of use, usability, aesthetics, and interactivity, respectively. Every part contains Likert-scaled questions, which range from 1 ("Strongly Agree") to 7 ("Strongly Disagree"), as well as open-ended questions to gather descriptive feedback. To assess the *internal consistency* and *reliability* of the questionnaire questions [23], Cronbach's alpha values were calculated for each evaluation metric across all modules. The recordings of simulated UI interaction are provided in Appendix C and the questionnaire questions can be accessed in Appendix B.

5.4 Reliability Analysis and Statistical Results

The Cronbach's alpha values regarding perceived usefulness, usability, aesthetics, interactivity, and perceived ease of use across all modules are 0.65, 0.62, 0.89, 0.89, and 0.73. Although a widely accepted value of Cronbach's Alpha is 0.7, 0.6 is also considered acceptable [22]. The statistic results can be found in Table 1 and Figure 11.

5.5 Result Analysis and Future Recommendations

For each criterion, the strengths, weaknesses, and future recommendations are analyzed based on the evaluation responses gathered from domain experts, which can be found in Table 2.

Table 2. Strengths, weaknesses, and recommendations for usefulness, usability, aesthetics, interactivity, and ease of use

Criteria	Strengths	Weaknesses	Recommendations
Perceived usefulness	• Most of the domain experts agree that the parameter setting panels are effective in allowing them to select desired parameters.	• One domain expert thinks that guidance on how to use the parameter setting panel is missing. • A domain expert has a problem understanding the parameters shown in the parameter setting panel.	• Provide guidance to explain the meanings of parameters and how to use the parameter setting panel.
Perceived usability	• More than half of domain experts find the organization and presentation of information clear and useful. • Domain experts think that the GIS map, data management table, and plots are effective.	• How to select the best policy for newly added pipelines is not clear in the Maintenance Policy Optimization module. • The pipeline data management table contains too many words.	• Give user option to select the best policy, reduce the number of words in pipeline data management and perhaps show the full length of texts only when expanded.
Perceived aesthetics	• Nearly every domain expert is satisfied with the aesthetic design.	• The colors of legends on the GIS map do not match with the colors of pipeline status	• It is recommended to follow a similar aesthetic design style as this design.
Perceived interactivity	• Most domain experts find the interactive features in this design useful in helping them interpret the plots and pipeline data.	• One of the domain experts thinks it is necessary to interact with the design by himself instead of watching the recordings.	• Conduct the user testing in person so that users can physically interact with the UI.
Perceived ease of use	• Most components of the design are easy to use for domain experts.	• The legends of severity levels on the GIS map are not intuitive enough since the colors used for legends are different from the colors on the GIS map.	• Modify the colors on the GIS map to match those of severity level legends.

Table 1. Statistics of UI evaluation responses

	Minimum	First Quartile	Median	Third Quartile	Maximum	Mean
Perceived usefulness	3.0	5.0	5.5	6.0	7.0	5.25
Perceived usability	2.0	4.0	5.0	6.0	7.0	4.775
Perceived aesthetics	4.0	5.0	6.0	6.0	7.0	5.5
Perceived interactivity	3.0	4.0	5.0	6.0	7.0	4.975
Perceived ease of use	3.0	4.0	4.0	5.0	6.0	4.35

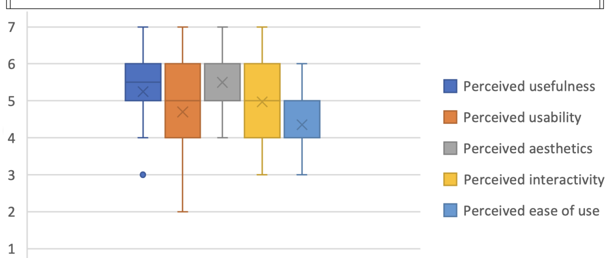

Fig. 11. Box plots of UI evaluation responses

6 DISCUSSION

This section delves into the research questions that are central to this study.

RQ1: What are the principles of design to incorporate in web UI design for sewer management web application?

Multiple principles from ISO 9241-151 were followed in the design, which can be found in Table 3.

According to the literature review, these are the principles for data visualization:

1. For data processing, it is important to divide complex data into short and easy-to-read fragments. This has been proven effective during the design process. Multiple domain experts expressed their preferences for short-fragmented data.

2. The charts should be selected based on the characteristics of the data and user preferences. For instance, the curve charts are most appropriate for visualizing the prediction of pipeline status. Pie charts and bar charts are most favored by domain experts for displaying pipeline network statistics.

3. Different strategies are to be adopted for color usage. Bright colors can be used to catch users' eyes, while light colors will de-emphasize elements. The background color needs to be distinguished to avoid distracting users. It is also essential to understand the cultural meanings of colors. For instance, blue, which represents integrity and reliability, is majorly used in the whole design.

4. To enhance interactivity, users should be allowed to add, remove, and alter items themselves, which has also been proven effective in the design of the parameter setting panel, pipeline data management table, and all the charts in the design. Interactivity can also be improved by linking different views. This method has been applied in many places in the design, such as the link between pipeline data management and the GIS map, prognostic charts and GIS map, etc.

Table 3. Principles followed in the UI design from ISO 9241-151

Navigation	• "Showing users where they are" [21]: In this design, users can clearly see where they are positioned because the background color of the navigation level where the users are is highlighted with light blue color. • "Choosing suitable navigation structure" [21]: In this design, information at a higher level of the navigation structures is emphasized by using a bolder and larger font. Signs that are commonly used in web navigation structures and familiar to users are adopted in the design, such as the expand button, close button, modify button, location button, and delete button. • "Providing navigation overviews" [21]: The navigation panel is permanently placed on the left side of every module, making sure the navigation component can be accessed by users at any time. • "Placing navigation components consistently" [21]: In the UI design, different modules share similar navigation design concepts. For instance, the navigation panel is placed on the left side of every module. The navigation buttons are all designed in deep blue. And the operation logic behind different navigation components is similar.
Layout	• "Consistent page layout" [21]: Each module in this design follows a similar layout. For instance, the navigation panel and the parameter setting panel are placed in fixed positions on the left side of every module. And the plots are positioned on the right side of every module. • "Place title information consistently" [21]: Titles are consistently placed in the top middle part of most components. Titles from the same kinds of components, such as prognostics charts, are displayed in duplicated font size and boldness. • "Identify all pages of a website" [21]: The logo of the organization is placed in the same position in every module so that all pages can be recognized by users.

RQ2: What are essential elements to include in the UI of sewer management web application?

Essential elements obtained based on the literature review on challenges and requirements in sewer management and interviews with domain experts can be found in Table 4.

RQ3: How does the UI design perform regarding perceived usefulness, ease of use, usability, aesthetics, and interactivity according to the modified Technology Acceptance Model?

It can be seen from Figure 11 that most of the responses are in the range of 5 to 6 for perceived usefulness and aesthetics. Moreover, by referring to Table 1, it is evident that participant responses to these two criteria have a mean larger than 5, which indicates the positive attitudes of domain experts towards the design. Responses on perceived usability and interactivity, however, lie in a smaller interval of 4 to 6. And responses from these two criteria both have a mean larger than 4 and close to 5, which has contributed to the neutral feedback from the participants. Responses on ease of use are distributed in the range of 4 to 5 and have a mean of 4.35, which is relatively low compared to other criteria. Nevertheless, it is still considered neutral in a 7-point Likert-Scaled system.

Some new ideas were identified from the participant responses, which are worth further consideration. The second participant provided a new perspective in which the statistics such as width, function, shape, and content can be displayed based on certain kinds of materials in pipelines. Another idea is to quantify the confidence band in the plots of the module of Prognostics, which is a valuable insight beneficial for domain experts to measure uncertainty levels.

7 CONCLUSION

The UI that incorporates web design principles and identified essential elements for sewer management received neutral to positive feedback from domain experts. Particularly, perceived usefulness and aesthetics received responses between 5 and 6, between 4 and 6 for perceived usability and interactivity, and between 4 and 5 for perceived ease of use. This indicates that ISO-9241-151 is an effective guide to follow for web UI design, and the identified data visualization techniques are advantageous in data visualization. It can also be concluded that the identified elements in the sewer management field meet the needs and expectations of domain experts.

8 FUTURE WORK

Several features can be further investigated and developed.

- The first is to provide guidance in understanding and using the parameter setting panel. This can be achieved by adding a guide button or by displaying guidance information when terminology is hovered over.
- The second is to enable users to choose the optimal maintenance policy for a pipeline. This could be complex since optimality involves the balance between cost, reliability, and life expectancy and requires the comprehensive consideration of experts. However, the visualization of the information needed can be presented to users to help with their decision-making process.
- The last is to cluster the pipelines that are spatially and geographically close. This is essential because domain experts want to make sure that those pipelines are maintained at the same time to reduce costs and disturbance to residents. This can be implemented by adding filters either in the parameter setting panel or the pipeline data management table.

Table 4. Essential elements to include in the UI of sewer management web application

GIS map	This element is essential in SAM. Through this map, the condition of the pipeline network is intuitively presented to domain experts. Detailed information on a specific pipeline can also be accessed by clicking. A GIS map is also critical to other elements of geospatial mapping, which maps various forms of pipeline data to geospatial data.
Parameter setting panel	This element is used in every module. Domain experts can use this panel to configure the parameters of models used to predict pipeline conditions, select different types of charts to present prediction results and choose the analysis level. This panel allows domain experts to customize parameters based on their needs and preferences and therefore enhance the flexibility and user-friendliness of the system.
Pipeline data management table	This table presents the filtered geospatial data, which includes pipeline location, shape, material, next inspection date, maintenance type, etc. This information is essential for domain experts to get a comprehensive understanding of the pipeline network and help with decision-making. This element also gives domain experts control over pipeline data, which can be added, deleted, removed, and modified to meet their needs.
Prognostics plots	Prognostics plots visualize the tendency of the probability of the pipeline being in a certain state over time. This information is critical for domain experts because it shows the development trend of pipeline status, the uncertainties of predictions, and key events where prominent changes in pipeline status might happen. Moreover, the x-axis, y-axis, and confidence band are interactive, and help guides are given to help users interpret the charts by clicking. The prognostic plots are helpful in improving domain experts' decision-making abilities.
Maintenance policy table	This table presents the maintenance actions needed for each pipeline under every policy, which is beneficial for domain experts in selecting the best maintenance policy.
Maintenance policy optimization plots	These plots include different metrics, such as cost, reliability, pipeline length, and number of pipelines. These metrics were selected based on user requirements. Similarly, these plots are interactive. Domain experts can be guided to interpret the plots by clicking on different components. These plots are also important for domain experts to make cost-efficient, risk-mitigated decisions.
Pipeline network statistics plots	Domain experts think having a comprehensive understanding of pipeline network statistics is vital to their decision-making. These plots include visual presentations of the proportions of pipelines of different materials, shapes, widths, functions, and content. Users are given the flexibility to choose various charts to visualize the data. These plots are also interactive, and data can be mapped to the GIS map just by clicking, which gives domain experts the freedom to interpret the statistics from multiple perspectives.

The evaluation of the UI can be conducted with a broader range of domain experts in the future. Only five domain experts in sewer management were involved in the evaluation process, which could lead to a lack of professional feedback on web design and overall representativeness. Therefore, it is recommended to conduct more extensive user evaluations with domain experts from both the sewer management and web design fields.

This research contributes to the web UI design for the sewer management web application, especially in the design of data visualization, web navigation, layout, and use of colors. Future work could focus on implementing web application based on this research. The recordings that show how users can interact with the UI can also be referenced, which can be found in Appendix C.

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A INTERVIEW

A.1 Requirements in sewer management

1. Do you think a web application would improve sewer infrastructure management? And why?
2. What are your goals when using an infrastructure management system?
3. What do you think can be improved in the current management system?
4. What key features and functionalities would you like to see in the water and sewer infrastructure management web application?
5. What key information about the infrastructure would you like to see in the web interface? Such as pipe condition, location, and inspection date.
6. What are your thoughts on elements that can be placed in the web user interface, such as GIS maps and graphs of network statistics?
7. What specific GIS functionalities or features would you like to see in the water and sewer infrastructure management web application?

A.2 Requirements in web design

A.2.1 Module of GIS.

1. What information would you like to see in GIS module ?
2. What forms are most effective in visualizing and managing the information?

A.2.2 Module of prognostics.

1. In an ideal prognostic tool, what information would you like to see at a glance?
2. What are your thoughts on visualizing the information?

A.2.3 Module of maintenance policy optimization.

1. What kind of information would you like to see in this module?
2. What are your thoughts on visualizing the information?

A.2.4 Module of network statistics.

1. What kind of statistics would you like to see in this module?
2. What kind of visualizations or data presentation forms would be most useful for understanding network statistics?

B SURVEY

B.1 Module of GIS

1. (Perceived usefulness) The parameter setting panel is useful as it allows me to select parameters from a wide range.
2. (Perceived usefulness) The GIS map is useful as it clearly shows

the status of the pipeline network.
3. (Perceived usability) The pipeline data management table is effective in selecting, filtering, deleting, exporting, and editing pipeline data.
4. (Perceived usability) The pipeline data management table presents data in a clear and easy-to-read format.
5. (Perceived aesthetics) The color scheme of the module of GIS is aesthetically pleasing.
6. (Perceived aesthetics) The design and layout of the module of GIS are aesthetically pleasing.
7. (Perceived interactivity) Interaction with the map (clicking on a specific pipeline) helps in a better understanding of the pipeline data.
8. (Perceived interactivity) The interactive features of this module are easy to understand and use.
9. (Perceived ease of use) I find the parameter setting panel easy to navigate and modify parameters.
10. (Perceived ease of use) The GIS map's legend and icons are intuitive and easy to interpret.

B.2 Module of Prognostics

1. (Perceived usefulness) Using the parameter setting panel is useful for me to select and modify parameters that suit my needs.
2. (Perceived usefulness) The prognostics plots are useful in visualizing the probability of a pipeline being in each state with pipeline age increasing.
3. (Perceived usability) The prognostics visualizations are effective in showing predictions of future pipeline conditions.
4. (Perceived usability) The organization and presentation of information in this module are clear and effective.
5. (Perceived aesthetics) The color scheme of the module of Prognostics is aesthetically pleasing.
6. (Perceived aesthetics) The design and layout of the module of Prognostics are aesthetically pleasing.
7. (Perceived interactivity) Interaction with charts (clicking on components) helps in a better understanding of the charts.
8. (Perceived interactivity) The interactive features of this module are easy to understand and use.
9. (Perceived ease of use) The user interface of the parameter setting panel is easy to navigate and understand, making it easier for me to define the parameters.
10. (Perceived ease of use) The design and layout of the prognostics plots are clear and easy to understand.

B.3 Module of Maintenance Policy Optimization

1. (Perceived usefulness) The parameter setting panel makes it easier to select and modify the parameters that suit my needs.
2. (Perceived usefulness) The plots are useful as it presents the information needed for optimizing maintenance policies, such as overall cost over policy and network reliability over policy.
3. (Perceived usability) The plots are useful as it presents a clear maintenance policy for each pipeline over time.
4. (Perceived usability) The organization and presentation of information in this module are clear and effective.
5. (Perceived aesthetics) The color scheme of the module of Prognostics is aesthetically pleasing.
6. (Perceived aesthetics) The design and layout of the module of Prognostics are visually pleasing.
7. (Perceived interactivity) The interactive features of this web application are easy to understand and use.
8. (Perceived interactivity) Interaction with charts (clicking on components) helps in a better understanding of the charts.
9. (Perceived ease of use) The layout of the parameter setting panel makes it easy for me to input the necessary parameters for maintenance policy optimization.
10. (Perceived ease of use) The visual presentation of plots is clear and comprehensive, which allows me to understand the data better.

B.4 Module of Statistics

1. (Perceived usefulness) The parameter setting panel makes it easier for me to select the type of chart and kind of data that best suits my needs.
2. (Perceived usefulness) The parameter setting panel in the statistics module is user-friendly and intuitive.
3. (Perceived usability) The generated charts are useful in providing insights and visual representation of the pipeline network data such as material, shape, content, and function.
4. (Perceived usability) The generated charts make it easier for me to interpret and understand the pipeline network data.
5. (Perceived aesthetics) The color scheme of the module of statistics is aesthetically pleasing.
6. (Perceived aesthetics) The design and layout of the module of statistics are visually pleasing.
7. (Perceived interactivity) The interactive features of this web application are easy to understand and use.
8. (Perceived interactivity) Interaction with charts (clicking on components) helps in a better understanding of the charts.
9. (Perceived ease of use) The user interface of the parameter panel is intuitive and user-friendly, making it easy to choose the combination between the type of chart and the kind of data.
10. (Perceived use of use) The design and layout of the generated charts are clear and easy to understand

C RECORDINGS

Recordings of simulated interactions can be accessed from the links below:
Module of GIS: *https://www.youtube.com/watch?v=XGLq9EMgaEE*
Module of Prognostics: *https://www.youtube.com/watch?v=l45AHOW5Soo*
Module of Maintenance Policy Optimization: *https://www.youtube.com/watch?v=SF6kh4hJ_ck*
Module of Statistics: *https://www.youtube.com/watch?v=BplsWiiyWu8*

D FINAL DESIGN

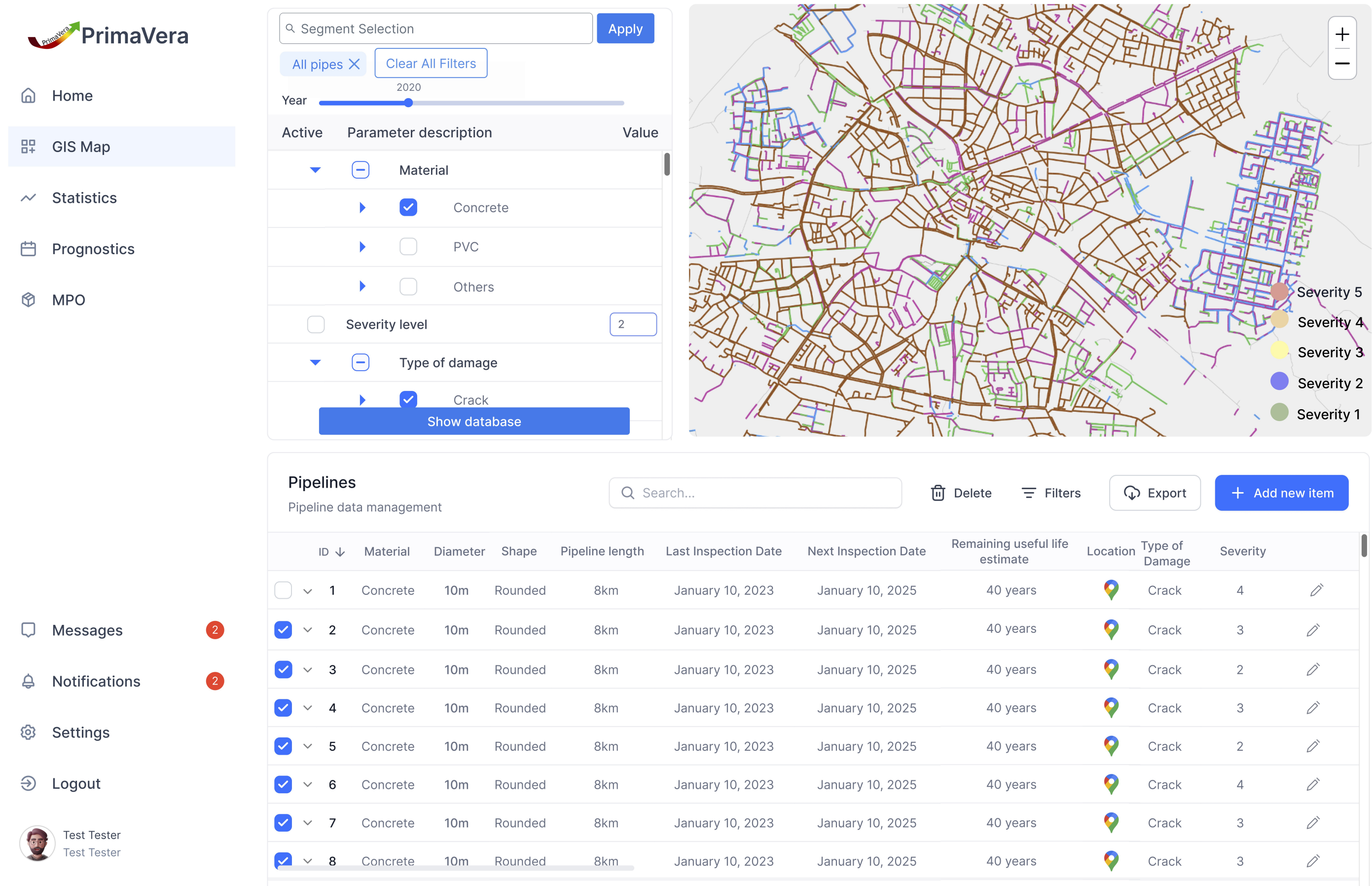

Fig. 12. Module of GIS

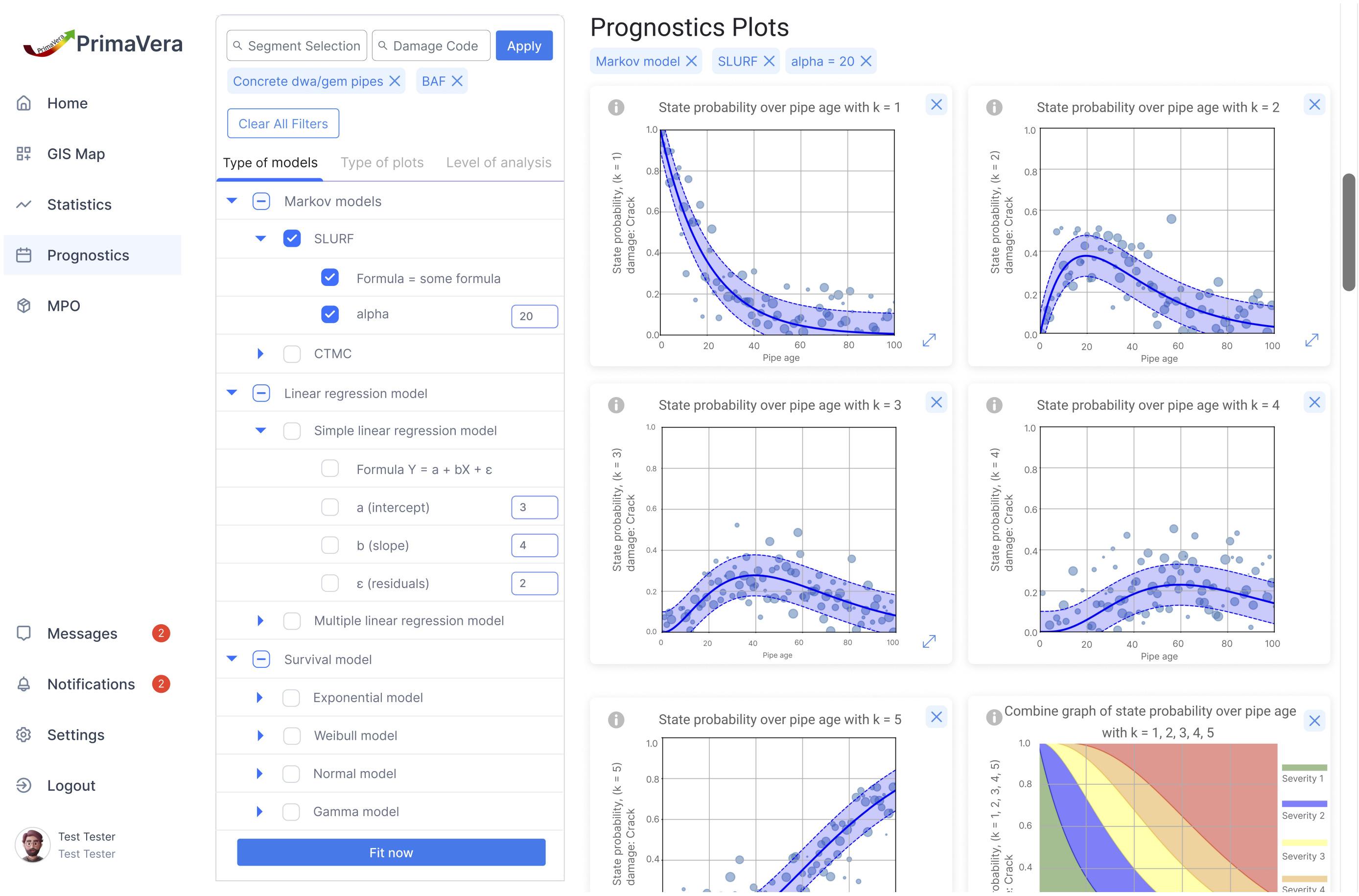

Fig. 13. Module of Prognostics

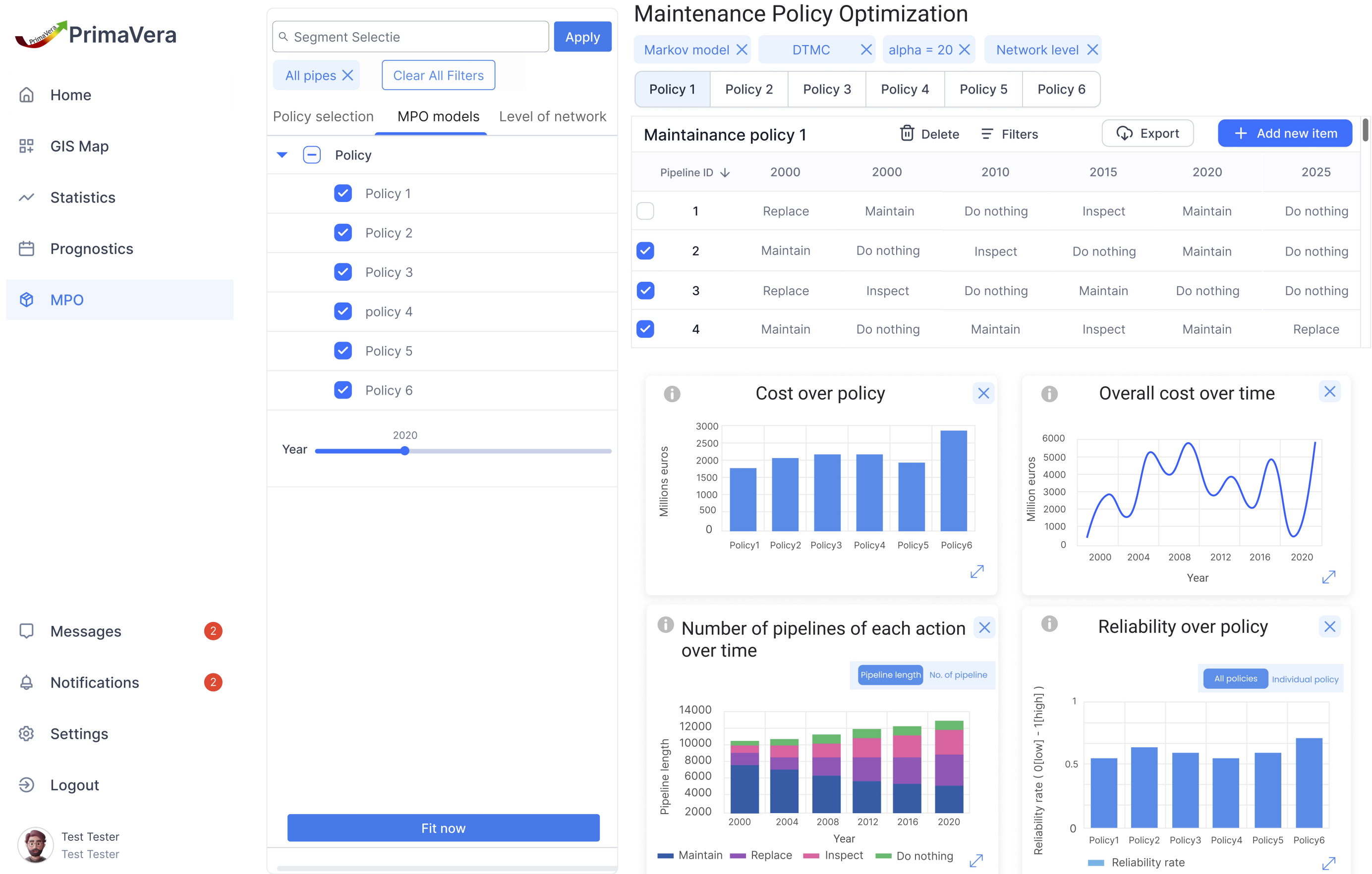

Fig. 14. Module of Maintenance Policy Optimization

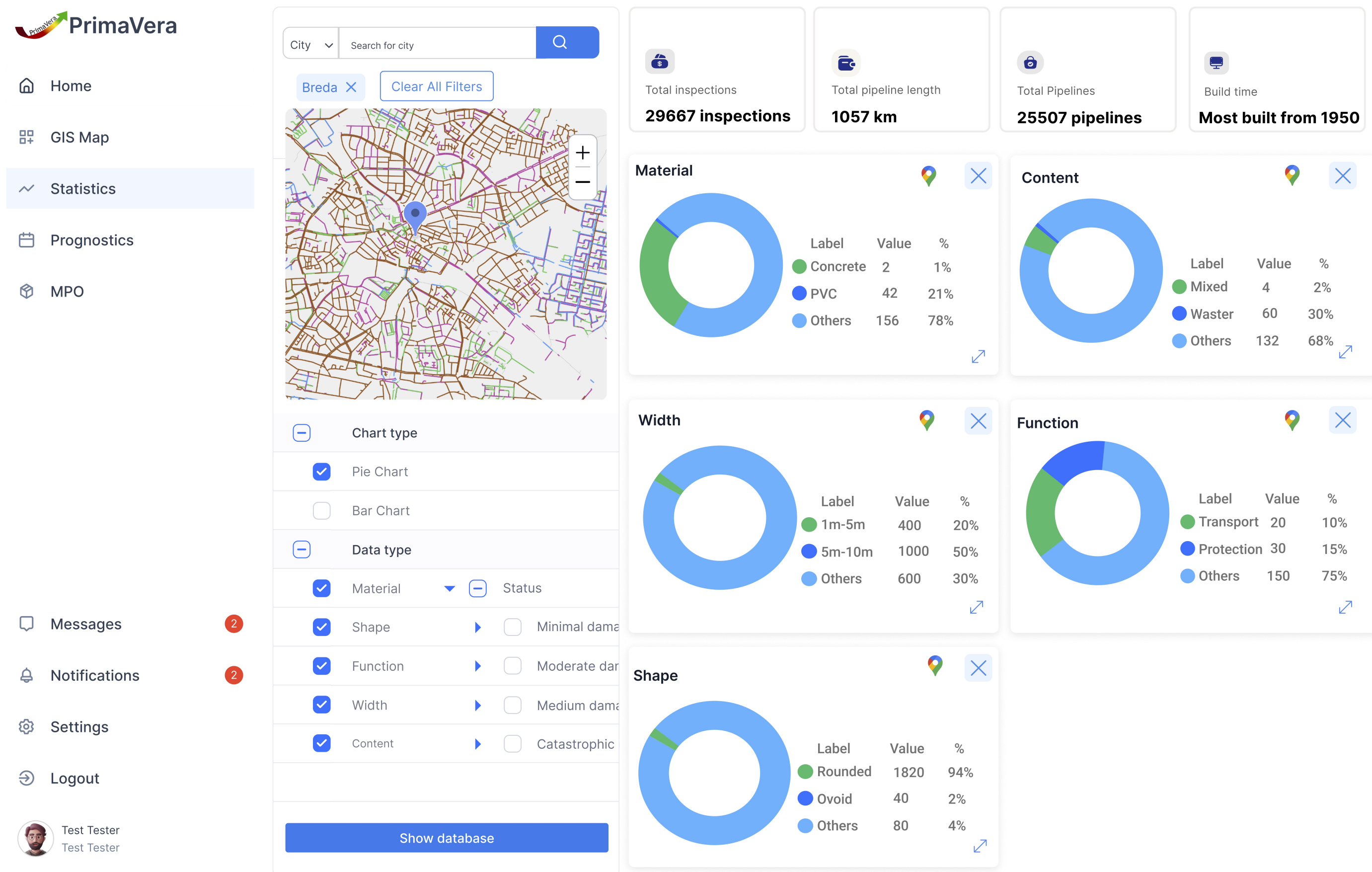

Fig. 15. Module of Statistics