ScaleVis: Interactive Exploration of Measurement Instrument Verification Data

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Abstract: Legal metrology ensures consumer protection from inaccurate measurements by regulating numerous instruments, some under EU harmonized legislation and others governed by national decisions based on the International Organization for Legal Metrology (OIML) recommendations. Verification laboratories produce measurement reports, often in unstructured PDF formats. Exploring and analyzing these reports remains inherently tedious and error-prone due to their format as numerous unstructured PDF files. To address these challenges, we introduce ScaleVis, a system combining standard and specialized visualizations to facilitate the exploration and analysis of measurement data including spatial information relevant to eccentricity measurements. The system incorporates data cleaning to resolve inconsistencies from manual entry and provides insights into measurement trends and deviations. Focusing on non-automatic weighing instruments, we analyze verification results to identify significant deviations in linearity and eccentricity. This study focuses on the analysis of non-automatic weighing instruments from various manufacturers and application domains. Using verification results from competent laboratories, we examine the metrological behavior of these instruments, identifying the ranges of linearity and eccentricities with the largest deviations from prescribed errors. A use case with domain experts underscores ScaleVis's potential to streamline data analysis in legal metrology, with initial feedback indicating strong utility and effectiveness.

1 INTRODUCTION

Metrology systems have different arrangements in relation to whether they are centralized or decentralized (distributed). This paper describes a distributed legal metrology system, i.e., metrological controls are performed by laboratories that are authorized to perform verifications of measuring instruments on behalf of the state in accordance with national regulations. These laboratories are required to inform the competent state institution about the verifications carried out by sending test reports confirming the compliance of the inspected measuring instruments in accordance with the prescribed requirements. Laboratories submit reports in the prescribed format to fulfill requirements set by normative documents. Based on these reports, a document database with the measurement results of all measuring instruments used has been established. However, the database represents only an history archive of data without any detailed overall analysis. Therefore, aware of the significant momentum in the digitalization of all processes and services offered on the market, digitalization in the field of legal metrology is also necessary (Oppermann et al., 2022). Existing databases can gain an additional purpose for various analyses that ultimately contribute to protecting the end consumer and speeding up monitoring processes. Efficient means of exploration and analysis are urgently needed.

In this work, we focus on non-automatic weighing instruments (NAWIs), verified in accordance with the requirements outlined in OIML Recommendation R76. Measurement data from three different types of NAWIs (precision scales, accuracy class II) produced by different manufacturers are analyzed to reveal load points that are most susceptible to significant errors,

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identify trends where certain load points may consistently exhibit larger errors, and enable comparisons between NAWIs from different manufacturers.

Interactive visual analysis is a well-established approach for understanding complex data. To facilitate insights into measurement reports, we employ a coordinated multiple views system. Our focus is on errors reported in three standard procedures: measurement errors under increasing load, errors under decreasing load, and eccentricity error measurements. Ideally, a scale should display consistent weight readings regardless of the load's position. Since eccentricity error measurement involves a spatial component, we account for this aspect when designing the corresponding visualization. In addition to the eccentricity error view, the system incorporates histograms, parallel coordinates, and box plots. All views are integrated into the coordinated multiple views system, enabling composite brushing to seamlessly link and explore data across multiple perspectives. We also briefly describe the preprocessing steps, which include extracting and cleaning data from the PDF files.

The system's design is the outcome of close collaboration between visualization and metrology experts. Through numerous discussion sessions, we identified key tasks and requirements, which are encapsulated in task abstractions and requirements specification. These insights guided the development of our visualization mappings and interaction design.

In this paper, our primary focus is not on introducing novel visualization techniques, but rather on leveraging the capabilities of coordinated multiple views (CMV) to explore complex metrology data. Given the vast amount of unstructured data available in various institutes that handle legal metrology, new exploration methods are urgently needed. The main contributions of this paper can be summarized as follows:

- ScaleVis, an interactive analysis tool for metrology data.
- Task abstractions and requirements analysis for measurement reports used in legal metrology.
- A use case that illustrates the usefulness of the proposed approach.

2 RELATED WORK

Interactive Visual Analysis (IVA) is an iterative approach to derive insights from large, multifaceted datasets, with linking and brushing as its core concept (Kehrer and Hauser, 2013), (Weber and Hauser, 2014). Introduced by Becker and Cleveland (Becker and Cleveland, 1987), brushing was expanded by Martin and Ward in XmdvTool, enabling logical operations like AND, OR, XOR, and NOT for composite brushes (Ward, 1994), (Martin and Ward, 1995). Coordinated and Multiple Views (CMV) extends this by synchronizing multiple data views, where actions like zooming, highlighting, or filtering in one view automatically update others (Roberts, 2007).

Aigner et al. (Aigner et al., 2011) provide an overview of tools and techniques for visualizing time-oriented data, including curve views and timelines. Although our data is load-dependent rather than time-dependent, we employ curve views, commonly used for temporal data.

Parallel coordinates plots (Inselberg, 1985) effectively display multidimensional data and are increasingly recognized beyond the visualization community. Our domain experts quickly adopted them due to their intuitive nature and minimal need for data transformation (Siirtola and Räihä, 2006).

While interactive visualization has been applied across various domains (Reina et al., 2020), its use in measurement-instrument verification is limited. This paper bridges that gap by introducing coordinated multiple views for metrology. Though visual analytics tools are widely used (Heer and Shneiderman, 2012), their application in metrology has mainly focused on consolidating data. We offer a novel contribution by advancing data analysis for legal metrology in a close collaboration with metrology experts.

The National Institute of Standards and Technology (NIST) emphasizes digitalization as a key driver for advancing measurement systems and compliance in legal metrology. As a significant challenge shaping the future of metrology, digitalization enables innovations like AI integration and data-sharing networks for managing and visualizing measurement data, highlighted at the 2023 International Conference on Weighing. National metrology institutes are developing strategies focused on digital, machine-readable certificates for verification and testing laboratories (Eichstädt et al., 2021), alongside algorithms to enhance data quality.

Studies have analyzed measurement results to assess non-conformity risks in NAWIs and evaluate risks for manufacturers and customers (Medina, 2018). These analyses include measurement results obtained in processes of type approval, verifications, and inspections. Also, there are related analysis, considering influences on measuring results like environmental conditions and measurement uncertainty obtained in processes of verification and calibration in laboratory controlled conditions and working on-side conditions (Memić et al., 2023).

3 BACKGROUND

Measurements are integral to daily life, whether tracking time, shopping, refueling, or monitoring health metrics. Metrology, the science of measurement, encompasses scientific, legal, and industrial branches. Legal metrology ensures accuracy and reliability, protecting consumers from fraud by maintaining measurements within prescribed maximum permissible errors (mpe). Countries determine priorities and instruments under state metrological supervision. WELMEC, the European Regional Metrology Organization, provides details on measuring instruments subject to legal metrology, including their regular verification intervals to ensure compliance with mpe. EU directives MID (2014/32/EU) and NAWID (2014/31/EU) govern harmonized instruments.

The OIML suggests expanding legal metrology to include additional instruments. This paper analyzes verification results of non-automatic weighing instruments (NAWIs) over an extended period. NAWIs, widely used in medical, retail, pharmaceutical, and industrial settings, are governed by the EU directive and verified per EN 45501 or OIML R76 standards. Accredited laboratories, meeting ISO/IEC 17020, provided data for this study. Verification confirms compliance through tests like repeatability, linearity, and eccentricity, ensuring adherence to prescribed errors.

Table 1 provides an example of measurement results following the OIML R76-2 recommendation, with error E calculated using these results. The measurement error for linearity and eccentricity is determined by:

$$E = I + 1/2e - \Delta L - L \quad (1)$$

To calculate the corrected error, the error E_0 (measured with an unloaded or near-zero load receptor) must be subtracted:

$$E_c = E - E_0 \quad (2)$$

During verification, NAWIs must satisfy the condition:

$$|E_c| \leq |mpe| \quad (3)$$

4 ANALYSIS TASKS AND REQUIREMENTS

In this paper, we focus on exploration and analysis of linearity and eccentricity. The linearity test is carried out throughout the entire measurement range of NAWI, i.e., the load points are evenly distributed throughout the entire measurement range and the maximum permissible error (mpe). The minimum number of load points taken into account when determining linearity errors is five, considering the smallest and largest weighing capacity. Eccentricity testing takes place in five load points, as shown in Figure 1, with a load corresponding to one-third of the maximum capacity of the subject NAWI.

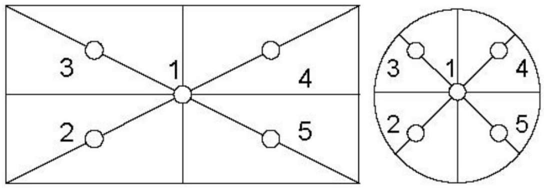

Figure 1: Predefined load placement positions for the eccentricity test on rectangular and round scales. The scale should show the same value regardless of load placement.

At the highest level, experts are primarily concerned with determining whether a measuring device meets the required normative document (OIML R 76). This initial assessment is straightforward—checking if all errors fall below the prescribed thresholds. While this analysis is essential, the extensive raw measurement data offers a wealth of additional insights. For a more exploratory approach, it is not enough to merely classify a device as compliant or non-compliant. Examining the distribution of the final corrected errors (Ec), even in cases where the thresholds are not exceeded, provides deeper insights and fosters a better understanding of the measurement data. The complete analysis refers to the requirements of final corrected errors (in further text referred to "error") in comparison to maximum permissible errors. This is precisely the goal of our work: to enable such in-depth exploration and provide tools that facilitate a comprehensive understanding of metrological data.

To inform our design, we engaged in a collaboration between visualization and metrology experts. Through numerous meetings and discussions, we identified key analysis tasks. Following the approach outlined by Brehmer and Munzner (Brehmer and Munzner, 2013), we systematically analyzed these tasks to derive essential requirements for our visualization design.

T1. Understand linearity errors, explore their development based on load, and analyze distributions categorized by manufacturer and time.

T2. Understand eccentricity errors and analyze their distributions based on spatial positions.

T3. Compare distributions of eccentricity and linearity errors.

T4. Gain an overview of the available data, including the number of manufacturers, years of measurement, temperature, and other supplementary

Table 1: An example of measurement results provided by approved laboratories, following the OIML R76-2 recommendation. The down arrow (↓) denotes measuring results obtained by progressively increasing loads, while the up arrow (↑) indicates measuring results obtained by progressively decreasing loads.

Load L in g	Indication I in g		Addition load ΔL in g		Error E in g		corrected Error E_c in g		mpe in g
	↓	↑	↓	↑	↓	↑	↓	↑	
0	0.0	0.0	0	0	0	0	0	0	0.025
5	5.0	5.0	0	0	0	0	0	0	0.05
50	50.0	50.0	0	0	0	0	0	0	0.05
200	200.0	200.0	0	0	0	0	0	0	0.05
300	300.0	300.0	0	0	0	0	0	0	0.05
400	400.01	400.01	0	0	0.01	0.01	0.01	0.01	0.05
600	600.01	600.01	0	0	0.01	0.01	0.01	0.01	0.1
610	610.02	610.02	0	0	0.01	0.02	0.02	0.02	0.1

data recorded in the measurement files.

Based on the tasks described above, the following design requirements are specified:

R1. Depict all linearity errors aligned to each other to be able to identify patterns.

R2. Visualize distributions of eccentricity errors taking spatial arrangement onto account.

R3. Provide means to see eccentricity errors correlations.

R4. Visualize distribution of errors and compare them.

- **R4a.** Support comparison of error development over time.
- **R4b.** Support comparison of error differences based on manufacturer.

R5. Visualize supplementary data to easy understand their distribution.

5 VISUALIZATION DESIGN

To address all the identified requirements, we employ a coordinated multiple views system. The data is structured in a table where each row corresponds to a measurement. For each measurement, we include supplemental data (e.g., year of measurement, serial number, age of the scale), maximum linearity error for an increasing load, maximum error for a decreasing load, eccentricity loads and their corresponding errors, and, as a special element, the linearity measurement data itself, represented as a measurement data curve. A similar data model has been described by Konyha et al. (Konyha et al., 2006).

Figure 2 provides a screenshot of the proposed views configuration. The histograms on the left display supplemental data and fulfill requirement **R5**, allowing experts to easily interpret the information.

The views in the second column of Figure 2 focus on eccentricity errors. The top view, referred to as the eccentricity error view, visualizes error distributions at each measurement point (**R2**). Initially, we attempted to represent these using five histograms in a row, but aligning each histogram with its corresponding position required additional effort. By overlaying the histograms on a map of the measurement points, the correspondence became immediately clear.

While the eccentricity error view effectively shows the distributions of individual errors, it does not clearly convey how the errors from a single measurement are related (**R3**). To address this, we propose using a parallel coordinates plot. This standard plot type supports highlighting when hovering with the mouse, making it easier to explore individual measurements. Such interaction is particularly useful because the errors have discrete values due to the digital nature and limited precision of the scales being examined. Notably, we maintained the axis order from one to five, as reordering (e.g., placing the axis one in the middle) proved confusing for domain experts. This confusion likely arose because left and right axes could not be placed unambiguously in that arrangement.

The curve views display linearity errors for all measurements (**R4**). Since measurements can involve different load values depending on a scale's range, we provide an option to normalize all data, mapping the horizontal axis to a standardized range from 0 to 1. Displaying all curves simultaneously allows users to examine errors within the context of the entire dataset. To address scalability issues, the view supports density mapping: when many curves are present, they are rendered with reduced opacity. This approach highlights the main trends effectively while retaining visibility of the overall dataset. Finally, we also show the

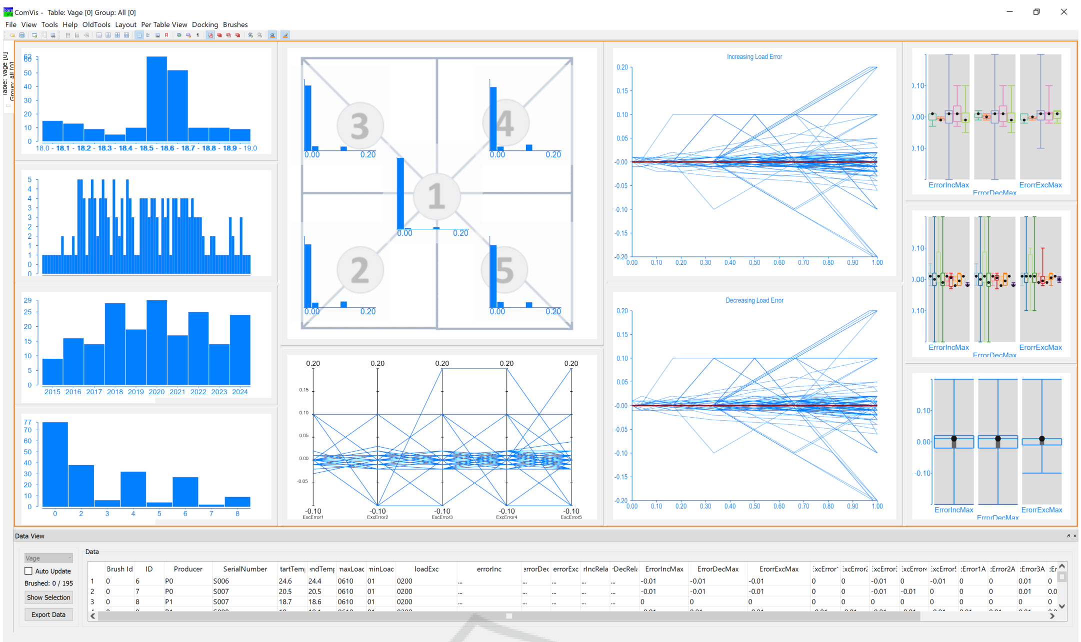

Figure 2: A screenshot of the view configuration used in one of the exploration sessions. The histograms on the left display various supplemental data. The central left column shows eccentricity errors, while the central right column presents linearity measurement errors for both increasing and decreasing loads. The box plots on the right show the distribution of errors in relation to the manufacturer (top), scale age (middle), and error distributions for all measurements (bottom). The table at the bottom shows the values of all dimensions.

zero line in red, so that users can easily see positive and negative errors.

On the right side of Figure 2, box plots illustrate the distributions of maximum linearity errors for increasing and decreasing load measurements, as well as for eccentricity tests. For eccentricity, the bottom view features a box plot for each error type and five separate box plots corresponding to the five eccentricity measurement positions. The two upper plots present error distributions for all three error types, split by manufacturer (top) and scale age (middle), addressing requirements **R4a** and **R4b**.

The data view at the bottom provides a tabular overview of all measurement data. When drill-down exploration is performed using composite brushing, the view display only the selected subset of data.

5.1 Interaction

All views in the system support linking and brushing, the fundamental principle of coordinated multiple views. Users can interactively select a subset of data in any view, and the corresponding items in all other views are automatically highlighted. Brushes can be combined using Boolean operations, enabling flexible and complex data exploration. The histograms allow for bin-based selections. In the parallel coordinates plot, brushing is performed by marking an interval

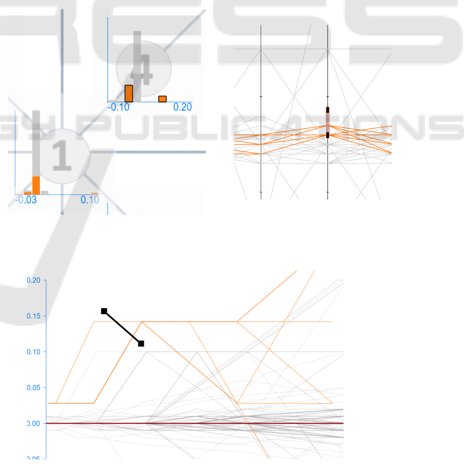

Figure 3: Users can brush histogram bins by clicking, select curves with a line brush, and define ranges in the parallel coordinates plot. Brushes are graphically represented, movable, and resizable, as shown by the black-bordered bins, parallel coordinates brush, and line brush in the curve view. Multiple brushes can be combined with Boolean operations.

along any axis. The curve views feature a specialized line brush, where the user draws a line, and all curves that intersect it are brushed. Figure 3 demonstrates these brushing techniques.

6 USE CASE

We describe a use case conducted by two visualization researchers and two metrology researchers, all of whom coauthor this paper. For this use case, we collected measurement reports from several approved laboratories in PDF format. These reports do not follow a standardized template; each laboratory uses its own format, but the format remains consistent for all tests conducted by a given laboratory. The reports are manually filled in by human operators, and as a result, they sometimes contain typographical errors, empty rows, or missing data. These inconsistencies highlight typical challenges encountered when dealing with data of unknown quality. The first step in our use case is data pre-processing.

6.1 Data Pre-Processing

Measurement reports from the NAWI Verification Data are stored in PDFs with inconsistent formats, varying in content, table structure, and result order. To address this, we developed Python scripts to extract data efficiently, ensuring consistency and reproducibility. These scripts currently support four widely used report templates based on the country of origin and can be extended for additional templates. Scanned documents are not included but could be supported in the future.

We processed 195 reports, creating an anonymized dataset by replacing manufacturers and serial numbers with randomized values to ensure privacy. While all measurements meet legal requirements, further analysis offers valuable insights for domain experts.

6.2 Interactive Visual Analysis

Once the data is processed, it can be loaded and analysis begins. The histograms of the supplemental data show, for example, how many scales are represented only once in the data set (each scale has to be tested on a biannual basis), how many are tested twice, etc. The highest number of tests is five, in our data set.

6.2.1 Exploring the Eccentricity Error

The eccentricity error view indicates different error distributions depending on the position. We show distribution of absolute errors (see Figure 2). Ideally, all data would fall into the leftmost bin, representing minimal errors. The central part of the scales, position 1 are most precise (which was somehow expected). Positions 4 and 5 exhibit slightly worse behavior compared to positions 2 and 3.

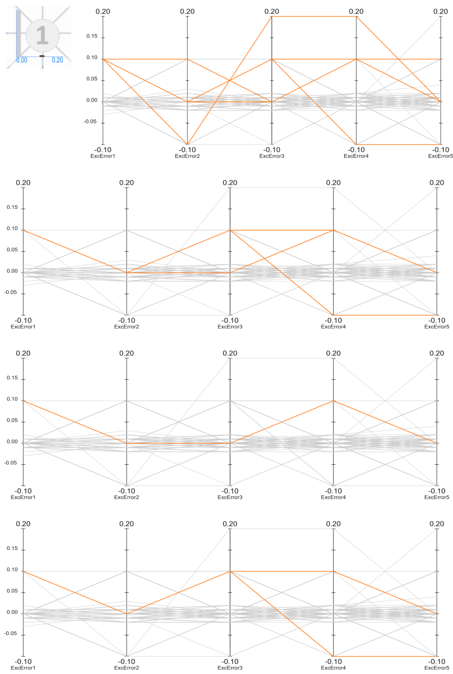

Figure 4: Exploring eccentricity errors across positions: We begin by brushing the high errors at position 1 by selecting the corresponding bin in the histogram, then refine the focus to cases with near-zero errors at position 2, identifying five distinct patterns before examining individual cases.

We brush high eccentricity errors at position one and examine the parallel coordinates to identify the other eccentricity errors associated with these cases. There are five measurements with the high error at the position 1. Figure 4 shows the brushed bin and the corresponding parallel coordinates in the top row.

The parallel coordinates plot shows the original error values, not the absolute ones. Notably, the five selected measurements display distinct patterns. To explore further, we drill down and refine the brush. Figure 4 also shows the results of these refinements. First, we analyze cases with medium errors at position 2. Three such cases are identified, and they again exhibit different error patterns. Further refinement isolates individual cases, allowing us to observe how errors vary across positions. One case in the final visualization shows a positive error at position 3, followed by negative errors at positions 4 and 5, for example.

These inconsistencies may stem from factors like measurement changes, operator errors, or other influences. Identifying such cases without visualization would be extremely challenging. Once detected, these cases can be thoroughly examined. If inconsistencies frequently occur for a particular scale type or are consistently reported by the same laboratory, further investigation may be required.

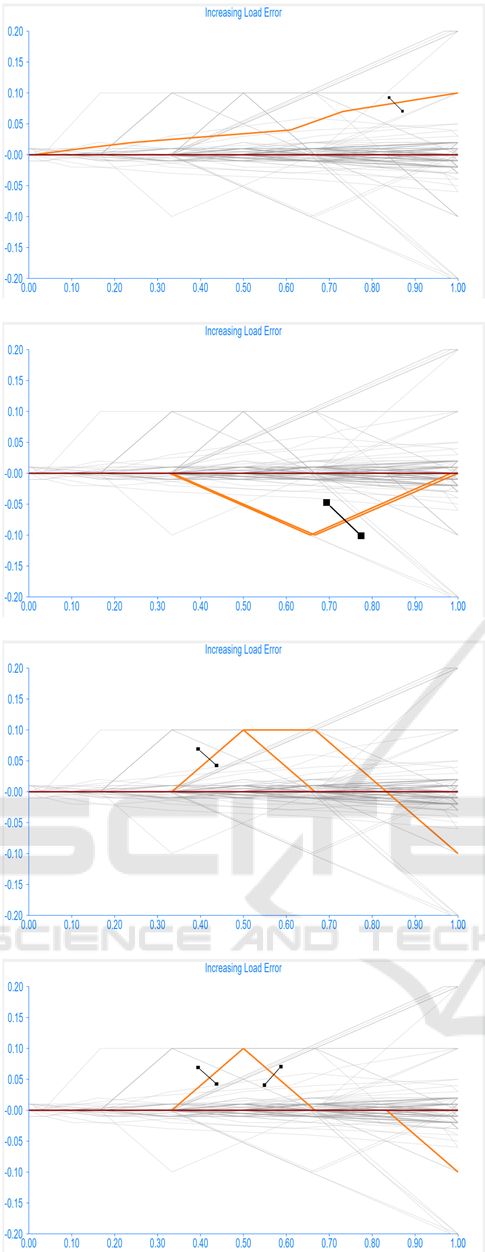

Figure 5: Exploring increasing load errors: While the error typically rises with load (top), some cases show unusual patterns, such as mid-measurement increases followed by decreases (second view) or early rises that fall to zero or negative values (third and fourth views). The line brush aids in selecting and analyzing these cases efficiently.

6.2.2 Exploring the Increasing Load Error

The curve view shows data for a series of measurements with increasing and decreasing load. As the load approaches the scale limits, we expect the absolute value of the error to rise. In the curve view (see Figure 2), we observe that most measurements

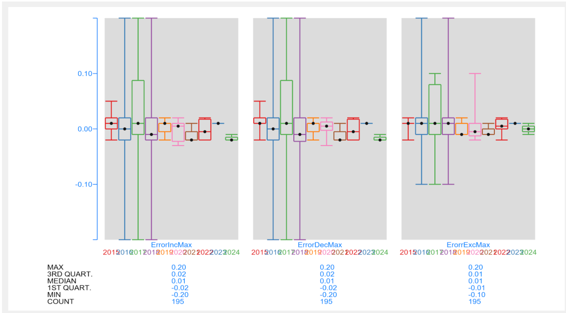

Figure 6: Box plots illustrate descriptive statistics, showing aggregated maximums of three measurements. Increasing and decreasing load measurements display similar behavior, while eccentricity exhibits consistent medians early on before oscillating in later years.

exhibit consistently low errors. However, there are a few cases with unusual behavior. Let us examine these cases now.

We use the line brush to select and analyze the curves. Figure 5 illustrates some interesting findings. The top view in Figure 5 shows a curve with a relatively high error for the largest load, where the error rises as the load increases. Although the error is high at the end, this behavior is expected.

The second view in Figure 5 highlights cases with a large negative error occurring mid-measurement, an unusual behavior with unclear causes. The next view in Figure 5 shows cases with a high positive error mid-measurement. Refinement reveals two behaviors: the error either drops to zero and turns negative or stays high briefly before becoming negative Such oscillations in error warrant further investigation.

6.2.3 Errors Across the Years

Finally, the box plots reveal several interesting insights. Figure 6 displays the distributions of the aggregated maximum values for increasing load, decreasing load, and eccentricity measurements over the years. The years correspond to when the measurements were performed. This view also provides quantitative data, if needed.

We observe different patterns in the data distributions for the loads. The increasing and decreasing load measurements exhibit oscillating median values. Larger minimum and maximum values were reported in the earlier years.

For the eccentricity load, the median remains very consistent during the first four years (2015–2018) before starting to oscillate. The largest minimum and maximum values also appear in the early years, but not consistently across all of them.

7 CONCLUSION

ScaleVis provides many benefits for the end user as well as in supervision of laboratories by metrology institutes in process of verification. Analysis of measurement data is a demanding task, but digitalization and visualization of metrology reports provides a faster insight into instruments deviations from the expected behavior, such as changes in the curve when testing linearity and eccentricity at different loads.

While these deviations are minor compared to permissible errors, visualization highlights instruments requiring further monitoring, crucial in sensitive applications like healthcare. Factors like hysteresis or improper handling often cause data deviations, improving the efficiency of metrological supervision. Visualization quickly detects anomalies in metrological characteristics for further investigation.

We used interactive visualization to explore the metrology data. The feedback from domain experts has been very positive, and we see the work presented in this paper as the beginning of a collaboration with the metrology experts who coauthored this paper.

Due to time constraints and data sensitivity, we started with a relatively small set of reports. Now that the usefulness of the approach has been demonstrated, we expect to gain access to a much larger corpus of data. The system has been designed to scale effectively with additional data, and all views have been proven to function with significantly larger datasets.

Given the scales' precision and digital data limitations, errors are numerically represented but from a limited set (e.g., 0.1, 0.2... with no intermediate values). To address overlapping data, we plan to explore scattering techniques in future research.

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