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Systems metrology in future cities – The example smart metrology campus (SMC)

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ABSTRACT

Future cities require complex metrological infrastructures to ensure core city development concepts such as liveability, sustainability and security of supply. Measurement devices are parts of multi-layered systems - from sensor networks up to the embedding and interactions of metrological systems with city society. Research in the field of Systems Metrology accounts for that fact by shifting the focus from single sensors to those interconnected systems, treating questions of data infrastructures, sensor networks, high level metrics and data communication. Research in the context of the PTB Smart Metrology Campus (SMC) is taking these trends into account. We will introduce the concepts and projects of the SMC on different system levels.

1. Introduction

Research directions that generalize metrological concepts to sensor systems and are tackling new challenges and opportunities arising from those systems are summarized under the keyword "Systems Metrology". Measuring systems embedded in city infrastructures in particular pose a variety of such challenges.

The paper depicts approaches to several of these challenges. Section 1 introduces systems metrology and gives an overview on smart cities and their measuring systems, as well as the idea of the Smart Metrology Campus (SMC). In the following sections, research subprojects are depicted that contribute to systems metrology on different system levels. These projects are self-contained, but can benefit from each other, as discussed in the conclusion in Section 6. The subprojects vary in their advancement, from setting up research questions and frameworks to proposing first solutions.

1.1. Systems metrology

Systems metrology is the science of measuring in networked systems, which consist of sensors, actuators, algorithms and measuring methods [1]. Its core scope is to make networked systems metrologically accessible and to progress the development of systemic metrological methods, especially in the context of quality infrastructure and regulation.

Metrological concepts such as uncertainty and traceability are extended to sensor systems and also made applicable to parameters that can no longer be directly traced back to physical quantities. This allows suitable metrics and critical values to be developed for such parameters, which serve as a secure basis for political, economic and social decisions.

Different systems levels pose different challenges. On the sensor network level, questions of network topology, quality assurance of low-cost networks and of sensor fusion by co- and self-calibration and reference sensors and many more arise and will be discussed in other places [2]. On the data level, integrating metrological information into complex data infrastructures is essential to ensure long-term and multi-purpose usability of measuring data (See Sec. 2). Models of the measuring system such as digital twins can aid in adding metrological information (see Sec. 3).

Above the technical system levels, the measuring system itself is embedded into larger systems such as a city infrastructure or a societal context. For the evaluation of those systems, high level metrics have to be defined and quality assured, e.g. by the integration of other data like human response (See Sec. 4). To ensure trust and acceptance of complex measuring systems in a societal environment, appropriate forms of communication of metrological data have to be developed (See Sec. 5).

1.2. Smart cities

In future cities, supply and monitoring networks are becoming more complex – and more sustainable by adding new concepts, such as prosumers and decentralization. Smart power grids can create grid stability through prediction and storage mechanisms, even when powered by renewable energies. At the same time, synergies are created between networks such as the energy and heating network and the mobility network. Environmental data such as temperature and pollutant and CO2 concentrations provide input for consumption forecasts as well as indicators for the effects of smart concepts on quality of life and sustainability. Numerous new research and task areas are emerging for systems metrology:

The complexity of network topologies is increasing and requires strategies to balance installation and maintenance costs on the one hand and measurement accuracy on the other [3]. Quality assurance in low-cost sensor networks must be ensured through appropriate data processing, enrichment with metrological metadata and reference sensors. Complex tasks - such as metrological early warning systems - are solved using AI methods. Digital twins bring validation and prediction potential.

The shift towards complex interconnected systems is leading to further changes in the scope of metrological research. New parameters such as sustainability and quality of life are used to evaluate measures

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and monitor effectiveness and must be placed on a metrological foundation. To achieve this, sensor data need to be linked to structural and statistical data as well as to subjective perception of the complex measuring instrument "human" [4].

At the same time, the communication of measurement data and metrological processes to society is moving to the fore: Smart supply and transport strategies, circular economy, re-use and recycling concepts need the initiative and support of a networked city population [5].

1.3. The Smart Metrology Campus

Due to the complexity of their interdependences, systems metrological methods have to be developed and tested with the help of demonstrators and real-life scenarios.

PTB, the national metrology institute of Germany, started an initiative to establish a smart city framework on their campuses in Braunschweig and Berlin. A data management system allowing the inclusion of metrological information is set up and tested on questions of energy efficiency and room climate measurements. The Smart Metrology Campus (SMC) will not only introduce technological advances in storing and sharing data, but also concepts to improve the well-being and participation options of its occupants.

Its vision is the intertwining of research activities, infrastructural needs and the involvement of its inhabitants.

2. Data infrastructures and systems engineering

The idea of systems metrology is the metrological development of connected systems and the introduction of concepts like uncertainty and traceability on a systems level. Both of those concepts require metadata about the sensor as well as the measurement condition and context. Data driven decision making without the integration of uncertainties and traceability can lead to erroneous or high-risk decisions, which can have big consequences in the domain of smart cities. The risk becomes even higher when the data driven decision making is processed by artificial intelligence. The challenges for systems metrology in smart cities lie in the large number and diverse range of sensors as well as the complex environment which can have an impact on the measurement.

2.1. A metrological data infrastructure for cities of the future

Data infrastructure provides the foundation for an organization to create, manage, use, and secure its data. One of its most critical roles is to ensure that the right data can get to the right users or systems at the right time to make effective data-driven decisions [6]. Central to this infrastructure is a robust data management system that automatically aggregates, stores, and semantically links sensor data and metadata. Common data management systems include a Data Warehouse, a Data Lake or a Big Data architecture. A suitable data management system would incorporate existing metrological metadata models like the Digital-SI (D-SI) [7] as well as digital calibration certificates (DCC) [8]. For instance, an electricity measurement would then not only encompass the numerical value but also metadata such as units and uncertainties encoded in the D-SI. This facilitates the seamless synchronization of disparate units, ensuring data consistency and accuracy. Moreover, each measurement would reference the specific electricity meter utilized, which would provide additional information regarding accuracy, possibly obtained through manufacturer specifications or DCCs. Other pertinent factors affecting measurement quality, such as installation temperature, could also be incorporated into the metadata.

The methodology employed for designing and implementing such a data management system is referred to as data engineering, which encompasses the development, implementation, and maintenance of systems and processes to transform raw data into high-quality, consistent information supporting various downstream applications, including analysis and machine learning [9].

2.2. Research environment and challenges

At the Smart Metrology Campus, the envisioned data infrastructure encompasses internal operational data, such as electricity consumption, internal research data from various projects, and external data sources like weather data. This comprehensive data will be made accessible to facilitate diverse research projects and operational applications. One research use case concerning energy which will be explained in detail in the next section.

The research combines the domains of metrology, smart city and data science. Research in all domains is required to solve the above-described problem and leads to the following research questions:

- How should a data management system be designed to store sensor data and relevant metadata, ensuring high trust, reliability, and security? This question encompasses considerations, including selecting an appropriate conceptual framework (e.g., Data Warehouse, Data Lake) and the technological implementation. The development also needs to consider the requirements of the stakeholders, such as data producers and data consumers, including the FAIR principles [10]. In addition, it should consider the operation and maintenance of the system for a long-term use.
- Which metadata needs to be included for later data evaluation? This involves incorporating information regarding sensor quality, calibration, and environmental factors influencing the uncertainty of the measurement. The challenges are to find and process the relevant information, which come from numerous different sources such as digital calibration certificates (DCC), manufacturer files but also supervising sensors.
- Which process or guide can be applied for the development of the data management system to ensure an optimal solution for the given and future use cases?

2.3. Systems engineering for a robust data engineering result

Addressing the third research question, a thorough examination of data engineering literature and methodologies from domains such as data mining, data science, and systems engineering has been conducted as described in Ref. [11]. Evaluation criteria encompassing requirements specific to smart cities and relevant data engineering considerations were taken into account. The Systems Engineering lifecycle outlined in the ISO 12588 [12] standard was identified as meeting all pertinent requirements.

The life cycle of systems engineering is split into the four phases: Concept Definition, System Definition, System Realization and System Deployment and Use. Each phase involves further sub-phases and is not strictly linear, but rather intended for iterative and agile development:

The Concept Definition phase is used to understand the context of what problem need to be solved and which additional requirements the concept needs to fulfil. The result of the concept definition should be the decision which kind of data management system can be used.

The System Definition then goes more into detail how this concept can be designed. In the context of data engineering this would mean to develop a draft how and with which technology this data management system can be implemented.

In the System Realization phase, the draft will then be brought into reality. This means the installation of hardware and software as well as the connection with different data producers and consumers. This phase also includes a verification and validation phase for the system to ensure the fulfilment of the requirements.

The last phase is called System Deployment and Use and it looks at the use phase of the system. This includes operational and maintenance aspects as well as the end of life of a system, which contains its transition and disposal phase.

2.4. Outlook

The resulting system which is developed will be designed in the context of a campus. For the use in smart cities, this system would of need to be scaled up. Another possible transition would be the development of several data infrastructures in a city which could then be connected via one or several data spaces. Data spaces enable data ecosystems based on equal data sharing, focusing on trust between participants, data sovereignty, and data interoperability [13].

The number of use cases illustrating how this provided data can be used is endless. The detailed description of the development of the data infrastructure via the systems engineering life cycle will be part of future work. This will especially include requirements and challenges of the metrological aspects. One use case - digital twins - will be explained in the following section.

3. HIGH-PERFORMANCE computing as a systems metrology use case – metrology as the basis for a digital twin

Today's society heavily relies on digital services and infrastructure. Simultaneously the energy demand of data centres in Germany that provide these services doubled over the last decade whilst energy costs also increased. This creates challenges both from an economic standpoint as well as from an operation standpoint with regard to energy consumption and cooling.

High-performance computing is a special use-case of a data centre where servers are combined in such a way that they can solve a given problem cooperatively. This is done if the problem size exceeds the capacity of a single machine or the wait time for the solution becomes too long.

A data centre has many sensors and measurement devices that track the conditions inside it, including sensors in the servers, temperature sensors both inside and outside, electricity meters, heat flow meters and more. Each sensor speaks a different protocol such as Modbus, M-Bus, wM-Bus, OPC-UA, REST with JSON or XML or other proprietary protocols. A Digital Twin [14] unifies access to the measurement data with a single interface. Many sensors do no provide metrological information such as the measured unit, but a Digital Twin can add such information.

The Digital Twin considered here consists of multiple components [15] that are separated into different networks for security reasons. Fig. 1 shows an overview of all components. The central component, the database resides in the centre in the standard network. All components directly related to the cluster are located in the corresponding cluster network and are accessed through a collector service in the standard network. This service also collects data from the outside world, like energy grid information and the current CO2 intensity of the energy grid. The Building Infrastructure Network contains all sensors that are related to the infrastructure on the campus. This network has higher security requirements to protect the infrastructure components. A collector service resides in this network, collects the data from the components within this network and send the data via a defined connection to the database.

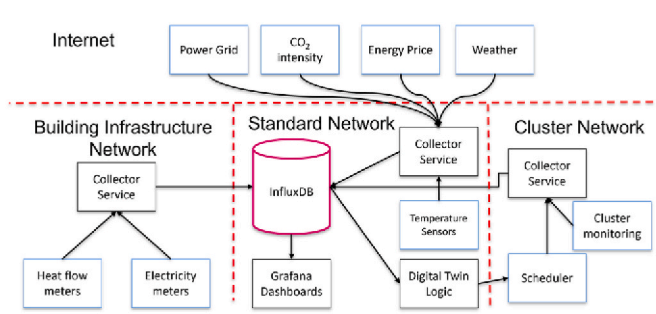

Fig. 1. The digital twin logic component.

The Digital Twin for HPC not only collects data but also uses the information to model the cluster behaviour and in turn provide information to the cluster. This is represented by the Digital Twin logic component (Fig. 1).

The Digital Twin is designed to help the operators improve the operation in terms of energy cost or CO2 emissions. HPC systems often rely on FCFS scheduling with backfilling. Using this strategy and the collected data, the digital twin looks for better points in the future to schedule a job. Two job traces were created using the Feitelson job model [16,17], one with a high utilisation and one with a moderate utilisation. Comparing the delaying strategy with the traditional FCFS strategy, savings of 2–4% for the high utilisation and 12–13.4 % for the moderate case can be achieved.

4. High level metric measuring models and human as a sensor

Smart cities have a multitude of sensors constantly recording data – how can this information be used to improve the well-being and quality of life of their inhabitants? Important categories such as 'well-being' are rather elusive because they are not well defined and made up of many different facets. While metrology has historically been concerned with the precise measurement of physical quantities [18], there is a growing interest in high-level metrics such as well-being. Such indicators are characterized by a multitude of influence quantities, which can significantly hamper efforts to measure them.

4.1. Introduction of the measurement approach

The subproject of the Smart Metrology Campus described here will explore how metrological principles can be applied to measure high-level metrics. For this, a conceptual model that is based on a classical metrological framework is being developed, which incorporates human observation alongside sensor data from indoor environments to establish a measure for well-being [19], a schematic of which can be seen in Fig. 2. In this model, the measurand is 'well-being in an office space' and the office space represents the measurement object. This object is characterized by environmental parameters obtained through sensors that monitor variables such as temperature, illuminance, and air quality. However, the space is not only affected by the measurable environmental parameters, but also by more qualitative factors such as office layout, cleanliness, social context, etc, which are referred to as influence quantities I.

Crucially, in this model, unlike many traditional approaches in social sciences and psychology where surveys or questionnaires are considered the measurement instruments, humans themselves serve as the

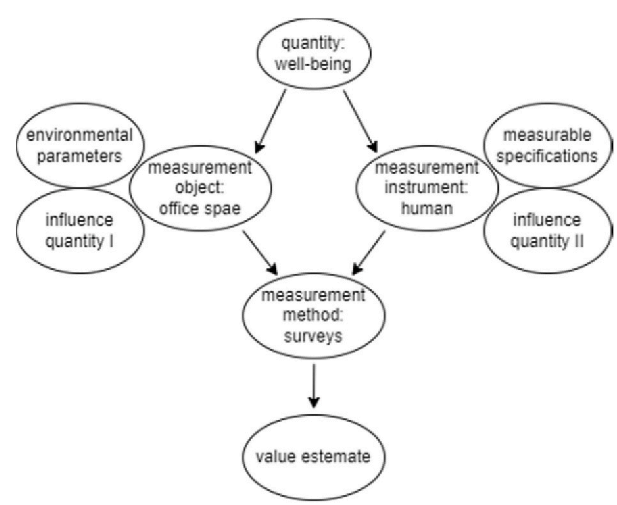

Fig. 2. Simplified measurement model, adapted from Ref. [19].

measurement instruments, based on an approach by Pendrill [20]. They provide subjective evaluations of their surroundings. Human observations introduce complexities stemming from biases, temporal variability, and individual differences in perception, which are referred to influence quantities II in Fig. 2. The proposed model aims to address these challenges by identifying and quantifying the various parameters influencing respondents to move them into the category of measurable specifications, thereby enhancing measurement accuracy.

4.2. Experimental methods and research questions

Experiments will be carried out in office spaces within the Smart Metrology Campus, utilizing a compact sensor setup to capture environmental data at desk-level. These data will be integrated into the Smart Metrology Campus's data infrastructure. The inhabitants of the workspaces act as the measurement instruments and will contribute to the measurement process by providing feedback through surveys.

With the proposed model and the information gathered by the experiments, the project aims to address how measurements that involve human perception can become more objective. This will be done by identifying the most relevant influence quantities and attempting to make them measurable. Additionally, a fundamental aspect of any measurement endeavour involves determining uncertainties. Assessing the potential to identify sources of uncertainties in the measurement and calculating them poses another intriguing question. Given the complexity of the system, which encompasses numerous influencing factors, pinpointing the origins of uncertainties and quantifying them at each step is a critical aspect of ensuring the reliability and accuracy of the measurement process.

4.3. Outlook

The interdisciplinary endeavour, comprised of metrology, psychology, and building science, seeks to bridge the gap between objective sensor data and subjective human experiences, to assess well-being in workplaces, through metrological methodologies, offering insights into factors influencing well-being in general. This knowledge could, for example, inform the creation of energy-efficient spaces without compromising the office residents' well-being. In addition, it is hoped that this model can be expanded to other non-traditional metrics such as quality of life in smart cities, which could contribute to the creation of more liveable urban environments.

5. Communication of metrology

Metrology and its measurement processes determine peoples' everyday life. Almost every activity does involve a measurement task in some way, e.g. in the morning while checking the weather prediction or the current traffic in the city before driving to work. Despite the numerous points of contact in everyday life, metrology is not a familiar topic for most citizens. As scientific research is often not directly perceptible to the public [21], measurement processes, their underlying concepts as well as their uncertainties remain hidden [22] and are difficult for citizens to understand.

Consequently, the Smart Metrology Campus aims to develop comprehensible ways of communication in order to promote public participation in the project. Citizens should be able to follow and understand project-related processes and progress. Regarding their role as non-experts, a target group-orientated communication of information is necessary to incorporate them into the project and promote a dialogue between science and society in general [23].

5.1. Forms of communication

Through digitalization the possibilities for communicating scientific information have grown and become diverse [24]. Especially visual forms of communication are considered a suitable way of illustrating scientific information and making it accessible to non-specialists [25]. This also applies in particular to the presentation of uncertainty [26]. Next to infographics and animations also interactive data visualizations have developed as an established and popular communication format [27].

A digital and interactive form of data visualizations which is also a common communication form for smart cities are *dashboards* [28]. Dashboards include a combination of text and graphics, while emphasising on graphics and diagrammatic forms of presentation [29]. Different forms of data, collected through various sensors, can be monitored at a glance and thus enable its audience a quick overview [30]. The information displayed is often available in real time and thus especially suited to continuous measurements [31].

Dashboards are mostly used for communication between scientists and experts or to support the internal functioning of processes and public services [28]. However, the use of dashboards goes beyond the internal communication between scientists and specialists. Citizen and non-specialist can also benefit from this form of communication. The design of a dashboards and the use of visual components to present the data obtained in a smart city makes it possible to identify relationships and dependencies and evaluate and compare data distributions [28]. Further, dashboards promote peoples' understanding, stimulate citizen engagements and enable public participation in decision-making [32].

5.2. Challenges

To fulfill these functions, there is a clear need to incorporate adaptability into the dashboard design to meet citizens' needs. Adapting a dashboard to different types of users is one of the biggest challenges in dashboards for smart cities [28].

Further, the communication and illustration of uncertainties in data can be difficult [33]. Due in part to the abstract nature of probability, understanding even the most conventional communications of uncertainty can be highly challenging — especially for novices [34]. Consequently, scientists fear that audiences will misinterpret the presentation of uncertainties in data visualisations and that this may affect their decision-making [35].

By integrating interactive features like clicking, sliding or zooming, citizens may perceive scientific abstract information more directly and personally meaningful by, which in turn facilitates understanding and learning of the information [36]. However, interactive visual forms of presentation are only considered successful if they are simple and easy to use and information can be processed effortlessly [24,37].

Last, the interpretation of scientific data visualizations is not only influenced by the content and the design of the dashboard, but also by the knowledge of the viewer. This includes e.g. their content knowledge, their general scientific understanding as well as their skill in dealing with visual data and forms like graphs and charts [38,39].

5.3. Research questions and objectives

Finally, more analytics with respect to how the user can interrogate and interpret the data are clearly required [31]. For visual representations, it is important that citizens effectively and efficiently absorb and process the information presented [40]. Despite this, „research on the effective visualization of scientific data through dashboards from a communication science perspective is scarce" [41].

Therefore, in the context of Smart Metrology Campus, we will examine how non-experts process scientific technological information and how they interpret this information. While developing an evidence-based Dashboard design, we want to crystallise comprehensive ways to illustrate different measurands as well as their uncertainties. After using social science methods for a process-accompanying evaluation, we also want to investigate if there are differences regarding the effect of different forms of visualization, e. g. whether people acquire a better understanding through interactive data visualizations and how they handle the illustration of measurement uncertainties. Do citizens feel more enlightened by certain graphic types? Or do they feel overwhelmed and not able to follow the project at all? Following these questions, further research interest is the extent to which citizens build up trust in the presented measurement data through the visualizations and whether this in turn can have an effect on trust-based decision-making processes (regarding smart cities).

6. Conclusion and outlook

Embedded within the interoperable data management system of the SMC, the sub-projects have the potential to incorporate additional data and be applied in various other scenarios. Further intertwined approaches within the SMC could aim to examine how effective communication of data could influence citizens' perception of their well-being and whether increased well-being through efficient communication has an impact on the participation of the citizens in the implementation of measures e.g., for energy saving. The setup of sensor networks apart from the room climate monitoring network in Section 4, e.g. an acoustics network to dynamically monitor noise load can provide future valuable additions to the research scope of the SMC as well. Thereby, their contribution to the promotion of more livable, resource-saving and future-orientated urban environments is not limited to the aims of the project.

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References

[1] PTB innovation cluster for systems metrology [Online]. Available: https://www.ptb.de/cms/en/research-development/ptbs-innovation-clusters/innovation-cluster-for-systems-metrology.html. (Accessed 15 April 2024).
[2] Tabandeh, S. et al. (unpublished) Sensor Network Metrology: Current State and Future Directions.
[3] S. Eichstädt, A. Vedurmudi, M. Gruber, D. Hutzschenreuter, Fundamental aspects in sensor network metrology, ACTA IMEKO 12 (1) (2023) 1–6.
[4] W.P. Fisher Jr., J. Melin, C. Möller, Metrology for climate-neutral cities. RISE REPORT 2021:84, RISE Research Institutes of Sweden, 2021.
[5] J. Anderson, L. Rainie, The Future of Well-Being in a Tech-Saturated World, Pew Research Center: Internet, Science & Tech, 2018. CID: 20.500.12592/wswbkg.
[6] What is data infrastructure? | glossary [Online]. Available: https://www.hpe.com/us/en/what-is/data-infrastructure.html. (Accessed 20 March 2024).
[7] D. Hutzschenreuter, F. Härtig, T. Wiedenhöfer, I. Smith, C. Brown, D-SI in short [Online].Available:https://www.ptb.de/empir2018/fileadmin/documents/empir/SmartCom/documents_for_download/D-SI_in_Short_2019-11-04_DE_PTB_NPL.pdf. (Accessed 20 November 2023).
[8] Digital calibration certificate - DCC [Online].Available:https://www.ptb.de/cms/en/research-development/ptbs-innovation-clusters/innovation-cluster-for-digitalization/kernziel1einheitlichkeitim/digital-calibration-certificate-dcc.html. (Accessed 20 November 2023).
[9] J. Reis, M.L. Housley, Fundamentals of Data Engineering: Plan and Build Robust Data Systems, first ed., O'Reilly Media, Sebastopol, CA, 2022.
[10] GO FAIR initiative [Online]. Available: https://www.go-fair.org. (Accessed 10 June 2024).
[11] M. Ulbig, D. Hutzschenreuter, B. Jung, Building trustworthy smart cities: a systems engineering approach to data engineering at the Smart Metrology Campus, Data-driven Smart Cities (DASC) (2024) (in press).
[12] 15288-2023 - ISO/IEC/IEEE International Standard Systems and Software Engineering–System Life Cycle Processes, IEEE, 2023.
[13] B. Otto, M. Hompel, S. Wrobel, Designing Data Spaces, 2022, https://doi.org/10.1007/978-3-030-93975-5.
[14] ISO Central Secretary, Digital Twin – Concepts and Terminology, International Organization for Standardization, Geneva, CH, Standard, Nov. 2023. ISO/IEC 30173:2023.
[15] A. Kammeyer, F. Burger, D. Lübbert, K. Wolter, Towards an hpc cluster digital twin and scheduling framework for improved energy efficiency, in: M. Ganzha, L. Maciaszek, M. Paprzycki, D.´Sl ̨ezak (Eds.), Proceedings of the 18th Conference on Computer Science and Intelligence Systems, Ser. Annals of Computer Science and Information Systems, vol. 35, 2023, pp. 265–268.
[16] D.G. Feitelson, Packing schemes for gang scheduling, in: D.G. Feitelson, L. Rudolph (Eds.), Job Scheduling Strategies for Parallel Processing, Springer Berlin Heidelberg, Berlin, Heidelberg, 1996, pp. 89–110.
[17] D.G. Feitelson, M.A. Jettee, Improved utilization and responsiveness with gang scheduling, in: D.G. Feitelson, L. Rudolph (Eds.), Job Scheduling Strategies for Parallel Processing, Springer Berlin Heidelberg, Berlin, Heidelberg, 1997, pp. 238–261.
[18] J.-P. Fanton, A brief history of metrology: past, present, and future. International Journal of Metrology and Quality Engineering, EDP Sciences, 2019, https://doi.org/10.1051/ijmqe/2019005.
[19] V. Peltason, J. Melin, B. Jung, Initial Steps toward a Metrological Model for Assessing Well-Being in Office Spaces, 2024.
[20] L. Pendrill, Man as a measurement instrument, NCSL International Measure 9 (4) (2014) 24–35, https://doi.org/10.1080/19315775.2014.11721702.
[21] M. Maier, L. Guenther, G. Ruhrmann, B. Barkela, J. Milde, Kommunikation ungesicherter wissenschaftlicher Evidenz – Herausforderungen für Wissenschaftler, Journalisten und Publikum, in: N. Janich, L. Rhein Hrsg (Eds.), Wissen - Kompetenz - Text: Band 13. Unsicherheit als Herausforderung für die Wissenschaft: Reflexionen aus Natur-, Sozial- und Geisteswissenschaften (S. 93–112), 2018. Peter Lang.
[22] Beat Jeckelmann, International system of units: concepts and current design, in: B. Jeckelmann, R.Hrsg Edelmaier (Eds.), Metrological Infrastructure (S. 1-6), De Gruyter Oldenbourg, 2023, https://doi.org/10.1515/9783110715835-201.
[23] M.S. Schäfer, J. Metag, Audiences of science communication between pluralisation, fragmentation and polarisation, in: B. Trench, M. BucchiHrsg (Eds.), Routledge Handbook of Public Communication of Science and Technology (S. 291-304), Routledge, 2021.
[24] E. Greussing, S.H. Kessler, H.G. Boomgaarden, Learning from science news via interactive and animated data visualizations: an investigation combining Eye tracking, online survey, and cued retrospective reporting, Sci. Commun. 42 (6) (2020) 803–828, https://doi.org/10.1177/1075547020962100.
[25] J. Metag, Visuelle wissenschaftskommunikation, in: K. LobingerHrsg (Ed.), Handbuch Visuelle Kommunikationsforschung, Springer, Fachmedien Wiesbaden, 2019, pp. 291–312.
[26] H. Griethe, H. Schumann, The visualization of uncertain data: methods and problems, Proceedings of SimVis (2006) 143–156.
[27] E. Bussemas, Mehr als Balken und Torten. Eine experimentelle Befragung zur Wahrnehmung von interaktiven Datenvisualisierungen im Journalismus, Medien & Kommunikationswissenschaft 66 (2) (2018) 188–216, https://doi.org/10.5771/1615-634X-2018-2-188.
[28] V. Contreras-Figueroa, L.G. Montané-Jiménez, T. Cepero, E. Benítez-Guerrero, C. Mezura-Godoy, Information visualization in adaptable dashboards for smart cities: a systematic review, in: Proc. 9th Int. Conf. In Software Engineering Research and Innovation (CONISOFT), 2021, pp. 34–43, https://doi.org/10.1109/CONISOFT52520.2021.00017. San Diego, CA.
[29] S. Few, Information Dashboard Design: Displaying Data for At-A-Glance Monitoring, second ed., Analytics Press, 2013.
[30] A. Sarikaya, M. Correll, L. Bartram, M. Tory, D. Fisher, What do we talk about when we talk about dashboards? IEEE Trans. Visual. Comput. Graph. (2018) https://doi.org/10.1109/TVCG.2018.2864903.
[31] M. Batty, A perspective on city dashboards, Reg. Stud. Region. Sci. 2 (1) (2015) 29–32, https://doi.org/10.1080/21681376.2014.987540.
[32] R. Matheus, M. Janssen, D. Maheshwari, Data science empowering the public: data-driven dashboards for transparent and accountable decision-making in smart cities, Govern. Inf. Q. 37 (3) (2020) 101284, https://doi.org/10.1016/j.giq.2018.01.006.
[33] J. Harold, I. Lorenzoni, T.F. Shipley, K.R. Coventry, Cognitive and psychological science insights to improve climate change data visualization, Nat. Clim. Change 6 (12) (2016) 1080–1089, https://doi.org/10.1038/nclimate3162.
[34] L. Padilla, M. Kay, J. Hullman, Uncertainty visualization, in: W.W. Piegorsch, R. A. Levine, H.H. Zhang, T.C.M. Lee Hrsg (Eds.), Computational Statistics in Data Science (S. 405-421), JOHN WILEY, 2022.
[35] J. Hullman, Why authors don't visualize uncertainty, EEE Trans. Visualiz. Comput. Graph. 26 (1) (2020) 130–139, https://doi.org/10.1109/TVCG.2019.2934287.
[36] O. Schroth, A. Dulic, S. Sheppard, Visual climate change communication:from iconography to locally framed 3D visualization, Environ. Commun. 8 (4) (2014) 413–432, https://doi.org/10.1080/17524032.2014.906478.
[37] Y. De Haan, S. Kruikemeier, S. Lecheler, G. Smit, R. van der Nat, When does an infographic say more than a thousand words? Journal. Stud. 19 (9) (2018) 1293–1312, https://doi.org/10.1080/1461670X.2016.1267592.
[38] S.R. Barnes, Examining the processes involved in the design of journalistic information graphics: an exploratory study, J. Vis. Literacy 36 (2) (2017) 55–76, https://doi.org/10.1080/1051144X.2017.1372088.
[39] R. McMahon, M. Stauffacher, R. Knutti, The unseen uncertainties in climate change: reviewing comprehension of an IPCC scenario graph, Climatic Change 133 (2) (2015) 141–154, https://doi.org/10.1007/s10584-015-1473-4.
[40] M. Burmester, A. Wenzel, in: W. Weber, M. Burmester, R. TilleHrsg (Eds.), Ansätze zur Evaluation interaktiver Infografiken, Springer Berlin Heidelberg, 2013. Interaktive Infografiken (S. 85-104.

[41] A. Schulze, F. Brand, J. Geppert, G.-F. Böl, Digital dashboards visualizing public health data: a systematic review, Front. Public Health 11 (2023) 999958, https://doi.org/10.3389/fpubh.2023.999958.

[42] QI-Digital [Online]. Available: https://www.qi-digital.de. (Accessed 10 June 2024).

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