



Publishable Summary for 18NET05 MATHMET Support for a European Metrology Network for mathematics and statistics

Overview

The objective of this network project was to support the associated European Metrology Network (EMN) for Mathematics and Statistics (EMN MATHMET). This was achieved by creating a Strategic Research Agenda (SRA), a stakeholder network and a Quality Management System (QMS). These activities have supported and accelerated the impact of the EMN MATHMET. This project also brought the associated EMN MATHMET to a position where it could become a point of reference for mathematics and statistics for metrology that includes input from stakeholders from industry, standardisation bodies and academia. Through this project, the associated EMN MATHMET has been supported in its promotion of best practices in mathematics and statistics for metrology.

European Metrology Network for Mathematics and Statistics (EMN MATHMET)

The precursor of the EMN MATHMET was the European Centre for Mathematics and Statistics in Metrology (MATHMET) which was established in 2014 as an outcome of the EMRP project NEW04 *Novel mathematical and statistical approaches to uncertainty evaluation*. Members from seven different EU countries joined this Centre, whose main activity was to hold a regular series of workshops and to prepare and facilitate EMPIR projects with a strong emphasis on mathematical and statistical methods. Approval for the present MATHMET Centre to become an EMN was agreed by the EURAMET General Assembly in May 2018. The MATHMET EMN was then established in June 2019 and currently has 14 NMIs, Dis and one partner that have signed the EMN Memorandum of Understanding (MoU).

Need

In the last decade metrology has expanded to address societal challenges related to energy, safety, climate, life sciences and health, using novel measurement modalities such as imaging, earth observation, spectroscopy and sensor networks. Model based software and mathematical algorithms have increasingly become an integrated part of measurement devices, necessitating the development of novel mathematical and statistical tools in metrology. This development includes uncertainty quantification of large sets of correlated data, handling complex systems, applications of machine learning, real-time simulations, forecasting for large-scale systems, virtual measurements and multi-physics modelling. The development of adequate mathematical and statistical tools addressing these challenges requires substantial effort that goes far beyond the capabilities of a single national metrology institute (NMI) and requires an EMN addressing these challenges. Thus in 2018 the EMN MATHMET for Mathematics and Statistics was approved by the General Assembly of EURAMET. However, in order to optimise impact, the EMN needs to strengthen its links to key stakeholders and to identify their most urgent needs, as well as to focus on mathematical support for the grand challenges of metrology and procedures for the assessment of software, data and guidelines.

Objectives

The overall aim of this project was to maximise and accelerate the impact of the EMN MATHMET. The project addressed the following objectives:

1. To develop an SRA for the EMN MATHMET that supports EU and EURAMET priorities by addressing the grand challenges in mathematics and statistics in metrology, e.g. large-scale and multivariate data analysis, new data analytics including machine learning, mathematical modelling, uncertainty quantification for large-scale metrology and virtual experiments and simulation.
2. To develop stakeholder consultation processes for the EMN MATHMET to enable it to identify the most urgent guidelines, software tools, virtual training and reference data in line with the SRA.
3. To create and implement a QMS that includes criteria and procedures for the assessment of advanced metrology software and guidance documents which ensures that the EMN MATHMET recommendations meet the highest quality levels and achieve wide use and substantial impact.

Results

Strategic research agenda (Objective 1)

As part of the development of the SRA, a survey was undertaken with members and stakeholders of the EMN MATHMET. This survey highlighted research topics in which stakeholders have interest and NMIs and DIs can offer their expertise. The research topics were then prioritised down based on the results of surveys of members and stakeholders of the EMN MATHMET:

1. Artificial Intelligence (AI) and Machine learning,
2. Computational modelling (CM) and Virtual Metrology (VM)
3. Uncertainty Quantification and Data Analysis

Two surveys on emerging research topics AI, CM and VM within the EMN MATHMET, were also conducted and analysed. The AI survey was aligned with the AI strategy of the European Commission and key topics for the further development of AI, CM and VM in metrology and its challenges were defined from the survey.

A joint stakeholder workshop was organised between MATHMET and the European Network for Business and Industrial Statistics (ENBIS) in 2021. ENBIS is a platform connecting individuals and organisations, interested in theoretical developments and practical applications in the field of business and industrial statistics. As part of the ENBIS workshop a general survey was distributed to attendees (> 100). The consortium optimised the use of this survey and extended it to include a part on the research topics for MATHMET (Objective 2). The results showed that stakeholder interest in the research topics was almost equal (44 % for Uncertainty, and 56 % for AI and Modelling and Simulation combined) and thus supported the choice of the research topics.

The project hosted an EMN Stakeholder Advisory Committee (SAC) meeting (Objective 2) with high level stakeholders in January 2022. At the meeting the research topics were prioritised, and stakeholder needs and challenges were discussed. Further to this, four separate interviews were conducted with SAC members ENBIS, the International Congress of Metrology (CFM), TNO and Infineon Technologies Austria on the project's QMS (Objective 3) and the research topics.

Based on the results of the above and the stakeholder consultation process (Objective 2), the project used its monthly meetings to develop a skeleton of the SRA, identify the challenges and needs of the research topics and assign lead authors for each topic (in order to produce a first draft of the SRA). The key challenge for the research topics was to increase trustworthiness of algorithms and assure the quality of the results, as this is central for stakeholders and policy makers. In order to increase trust in algorithms, a number of challenges were identified (i) uncertainty quantification, (ii) robustness, (iii) interpretability, (iv) reliability and (v) efficiency.

As well as the research topics in the SRA, it was also important to align this with the quality criteria for data, software, algorithms and guidelines, as developed in parallel in the project's QMS (Objective 3).

The draft SRA was completed by July 2022 and distributed to the signatories of the EMN MATHMET MoU, EURAMET TCs, EMNs, EURAMET and the EMN MATHMET SAC for feedback. The draft SRA was also presented at conferences and workshops, where stakeholders were invited to provide their feedback e.g.:

- IMEKO-MATHMET 2022 Joint Symposium in Porto and IMEKO TC6 in Berlin (both Sep 2022),
- EMN Climate Observation and Ocean (COO)/ EURAMET TC Virtual pavilion at the Climate Action Workshop (Sep 2022),
- The AGM of the EMN Advanced Manufacturing (Oct 2022),
- the international MATHMET conference in Paris (Nov 2022).

Based on the feedback from the above discussions plus that from the Institute of Measurement Science of the Slovak Academy of Sciences (IMS SAS), WELMEC, EUROLAB, CFM, SMD (Belgium NMI), CEM (Spanish NMI), and EURAMET's General Assembly, and from the EMN SAC, the SRA was revised to include:

- additional applications and use cases based on stakeholder needs
- a brief description of the quality assurance tools (QAT, Objective 3) and the relation to the SRA
- a link to FAIR principles
- a description of the stakeholder consultation process (Objective 2).

The final SRA was presented at the joint ENBIS-MATHMET conference in May 2023 in Turin (MSMM 2023) and was approved by Euramet's BoD in July 2023.

Stakeholder consultation processes (Objective 2)

The goal of the stakeholder consultation processes was to identify the most urgent stakeholder needs in the field of mathematics and statistics in metrology and to use the information for developing the SRA (Objective 1) and the QMS (Objective 3).

To begin with a MATHMET stakeholder database was created and the stakeholders prioritised. A subset of high-level priority stakeholders was then chosen (stakeholder mapping) for first contacting as per the project's developed communications plan. Overall, three types of stakeholders were defined:

- the metrology community that interacts with MATHMET partners in a service / support capacity, such as metrology organisations, EURAMET TCs, accreditation bodies, and other EURAMET EMNs,
- the users, such as those from industry, energy, environment, and healthcare and academia, who ultimately benefit from MATHMET,
- all other users, who could benefit from MATHMET in the in the longer term.

For more efficient and successful stakeholder engagement different engagement approaches were selected for the different stakeholder types i.e. consultation, push (e.g. emails) and pull (website) communications.

Two questionnaires were developed for stakeholder consultations and to help integrate stakeholder needs into the SRA and QMS (Objectives 1 & 3):

1. A short questionnaire was used as preparation for stakeholder face-to-face interviews. This short questionnaire was attached to the first email sent to stakeholders together with a short description of the EMN MATHMET. The main purpose of this short questionnaire was to find out the research interests of a particular stakeholder ready for the face-to-face interviews.
2. A longer detailed questionnaire was used to define the research needs of stakeholders. This longer questionnaire could be used in two ways:
 - If the stakeholder did not wish to have a face-to-face interview (or was a lower priority stakeholder), it could be used to find out as much as possible about their research needs.
 - If the stakeholder is due to have a face-to-face interview, a modified version of longer questionnaire could be used as preparation for this interview. The modification of the longer questionnaire depended on the answers of the stakeholder in the short questionnaire.

A key activity in the stakeholder consultation process was the setting up of the EMN SAC. For efficient communication with the high-level stakeholders from the SAC, relationship managers were selected from the project's consortium. The relationship managers were also part of the EMN's communications team and

responsible for engagement strategy. The stakeholders in the EMN MATHMET's SAC are: EMN COO, WELMEC, EUROLAB, UKAS, TNO, ENBIS, Infineon Technologies Austria, CFM, Eurachem and the Technopolis Group. These stakeholders cover the project's research topics (Objective 1).

Following the set-up of the EMN SAC, meetings were used by the project to gain feedback on the SRA (Objective 1), road maps, and further priorities related to urgent needs for software tools, reference data, training and guidance in mathematics and statistics in metrology (Objective 3).

As stated in Objective 1, the project used a joint MATHMET – ENBIS Stakeholder workshop in 2021 to gain stakeholders input and to stimulate further stakeholder interest and consultation. At the workshop the EMN and the project's QMS (Objective 3) and its application to use cases was presented to stakeholders in a special round table session in which feedback was actively sought.

Further to this the EMN hosted an international MATHMET Conference in Paris (Nov 2022) and in particular a round table session which was used to gain feedback from stakeholders on the draft SRA (Objective 1) and on how further and better engage with the EMN MATHMET. The participants included: BIPM's Joint Committee for Guides in Metrology (JCGM) Working Group on the Expression of Uncertainty in Measurement (JCGM-WG1:GUM), EURAMET Technical Committees for Interdisciplinary Metrology (TC-IM), Thermometry (TC-T), Photometry and Radiometry (TC-PR), Mass and Related Quantities (TC-M) and Electricity and Magnetism (TC-EM), EMN Radiation Protection, EMN Smart Electrical Grids, EMN Advanced Manufacturing, EMN-Quantum technologies, ENBIS, JCMwave GmbH, TNO, and Infineon Technologies Austria.

The final SRA (Objective 1) and QMS (Objective 3) were presented to stakeholders at the MSMM conference in Turin in May 2023. This important event marked a major milestone for the project and EMN and their commitment to stakeholder engagement.

Finally, a website for the EMN MATHMET was launched in 2022 <https://www.euramet.org/european-metrology-networks/mathmet/>. The website provides stakeholders with an information hub for mathematics and statistics in metrology, as well as details of the EMN and its current and future activities.

Quality management system (Objective 3)

A QMS renamed quality assurance tools (QAT), was developed that provides documented rules ensuring the highest quality of software, data and guidelines developed by the associated EMN MATHMET.

To begin developing the QMS, gap analysis was used to identify the areas where current practice related to guidelines, software and data quality in metrology did not meet best practice in other science domains and where that current best practice did not meet the needs of the metrology community for the research topics identified in Objective 1. Gaps were identified in the following areas:

- **General**
 - Reproducibility of computing environment (e.g., docker),
 - Scalable QM processes (i.e., light weight to full weight depending on problem)
 - Metrics to assess problem complexity
- **Data**
 - Data readiness levels
 - Quality standards for data
 - Version control
 - Data usage risk assessment
 - Data profiling, reporting and repair
- **Software**
 - Software Certification
 - Software Traceability

Based on the gap analysis and the current best practices, a requirements document and criteria that outlined the QMS was developed. The QMS took an ISO 9001:2015 process-based approach and its overall aims were to (i) ensure MATHMET data and software is fit-for-purpose, (ii) not be over-prescriptive, (iii) require formality where essential, e.g., a common format for specifying mathematical calculations, and (iv) draw on procedures used within partners' institutions and existing QMS standards. The last point (iv) is key and to reflect this the

QMS consists of a framework (or skeleton) designed to accommodate the QMS' used within the partners' organisations (e.g., version control will be required, but no specific version control method will be mandated).

The skeleton QMS was applied to six use-cases for metrology software, in order to gain feedback on its use:

1. CASoft: Enables risks associated with decision-making in conformity assessment to be managed when measurement uncertainty is to be taken into account (<https://www.lne.fr/en/software/CASoft>).
2. Software developed within the EMPIR 17IND12 Met4FoF project, which performs metrological data analysis and uncertainty calculations for sensor networks and for problems involving machine learning.
3. Pressure Gauge Calibration: Used for the evaluation of measurement uncertainty for results of calibration of pressure gauge (electromechanical and mechanical manometers).
4. PyDynamic: Provides a starting point for users in metrology and related areas who deal with time-dependent, i.e., dynamic, measurements (<https://pypi.org/project/PyDynamic/>)
5. RBD Homogeneity: For assessing reference material homogeneity data acquired via a balanced randomised block design, as described in ISO Guide 35:2017.
6. LNE Uncertainty: Software to allow the evaluation of measurement uncertainty according to the framework of the GUM and its Supplement on a Monte Carlo method.

The joint MATHMET-ENBIS workshop (Objectives 1 & 2) was used to gather stakeholder feedback on the skeleton QMS. The feedback from stakeholders included: (i) it is vital that details of the QMS (e.g., templates and use-cases) are made available on the EMN MATHMET website, (ii) can the QMS be used to help develop open datasets and open software and feed into relevant technical committees?, (iii) the QMS must require any open software and open datasets that are used to be clearly acknowledged, and (iv) the use-cases will help create trust in the QMS and they should be made available on the EMN MATHMET website. The QMS was then updated based on this feedback.

For the Guidelines component of the QMS, a process and associated checklist were developed to help ensure a sufficient level of quality in the development, assessment, and recommendation of existing and future guidelines for mathematics and statistics in metrology. The guidelines document and checklist were reviewed by the consortium and multiple test-cases were identified for partners to apply the guidelines QMS and provide further feedback.

For the data and software components of the QMS, PDF templates were developed, that interactively guide the user through the process of creating a quality plan for a dataset or piece of software. The templates were also distributed to project partners for testing and feedback, and a test plan distributed to help ensure testing consistency.

Risk assessment is also a key element of the QMS, and for data and software, risk is quantified using a value called an integrity level. The integrity level is a number between 1 and 4, where 1 indicates the lowest level of risk (e.g., prototypes of software for internal use within an organisation) and 4 indicates the highest (e.g., software that is safety critical). The PDF templates in the QMS help users assign and review an integrity level. The integrity level is used to determine the quality management activities, i.e., the activities listed on the plan, that shall be undertaken (e.g., reviews required and whether they should be independent of the developers of the dataset or software). A linked document provides further details of the QMS and further reference material.

The QMS, renamed quality assurance tools (QAT), is available for stakeholders to download and use from the EMN MATHMET website ([here](#)).

Impact

The network infrastructure developed in this project has supported the success of the associated EMN MATHMET, providing it with important basic tools for promoting best practice in mathematics and statistics for metrology. Via the outputs developed in this project the SRA (Objective 1), stakeholder consultation (Objective 2) and the QMS (Objective 3) the associated EMN MATHMET has received a kick-start in tackling the grand challenges and emerging fields in mathematics and statistics for metrology.

Direct impact

This project has involved stakeholders in an extensive consultation (Objective 2) to help identify the most urgent needs for mathematics and statistics in metrology and support the associated EMN. The project has also used its impact activities (e.g. presentations, workshops, publications, training courses to disseminate the EMN to a wider audience. Such stakeholder engagement has included:

- An international MATHMET conference was hosted by IPQ in Lisbon in Nov 2019. More than 50 participants presented and discussed contemporary methods and challenges in applications of mathematical models and statistical data analysis to measurement science.
- The first international workshop on Metrology for virtual measuring instruments VirtMet21 was jointly organised by PTB, the EMN Advanced Manufacturing and EMN MATHMET. More than 70 participants discussed simulations, virtual experiments, digital twins in metrology, quality assurance and industrial applications.
- Two training courses on measurement uncertainty were organised by PTB and INRIM in Nov 2019 and Mar 2020. The training courses were attended by more than 20 attendees from academic and scientific communities.
- In Sep 2022 a joint IMEKO-MATHMET symposium was held at which the SRA and QMS were presented to and discussed with stakeholders.
- An international MATHMET conference was hosted by LNE in Nov 2023 with more than 80 participants.
- A 2-day introductory training course for the QMS, organised by NPL and VSL was held in Mar 2023. There were approx. 50 delegates, who were provided an overview of the QMS, examples of quality plans and the opportunity to discuss their own applications. Presentations from the course have been uploaded to the BIPM e-learning platform and are now publicly available.
- In May 2023 the final SRA and QMS were presented as part of the MSMM-2023 workshop in Turin, organised by INRIM. There were 72 registered participants.

Further to this, the project has provided input to standards bodies ISO TC 158, CEN TC 264, UNI CT 016 Quality management and statistical methods, the Eurachem Measurement Uncertainty and Traceability Working Group, ISO TC 69 Applications of statistical methods, and the BIPM and CIPM JCGM WG1.

It has also provided input to EC DG CONNECT- digital single market on a White Paper on Artificial Intelligence - A European approach to excellence and trust: COM (2020) 65 final. As well as feedback to EA (European Accreditation) on a proposed revision of EA-4/02 on uncertainty evaluation.

The feedback from this project's stakeholder consultations and the above impact activities was directly used in the developed of the SRA (Objective 1) and QMS (Objective 3) and to ensure they both address stakeholder needs. In the longer term, the feedback from the stakeholder consultations can also be used by the EMN MATHMET to better target its future support for stakeholders in mathematics and statistics in metrology. In particular, the SRA (Objective 1) will support the EMN MATHMET to direct future research activities to stakeholder needs, which in turn should increase the efficiency of the EMN in supporting necessary research developments and grand challenges at the European level

The QMS (Objective 3) developed in this project was developed to (i) ensure MATHMET data and software is fit-for-purpose, (ii) not be over-prescriptive, (iii) require formality where essential, e.g., a common format for specifying mathematical calculations, and (iv) draw on procedures used within partners' institutions and existing QMS standards. The QMS includes criteria and procedures for the assessment of advanced metrology software and guidance documents which in turn will ensure that the recommendations of the associated EMN can be based on the highest quality levels. The publication of the QMS (QAT) on the EMN website has also made it available to all stakeholders, including other institutions who can use them for improving the quality of their own work. Indeed, the EMN's QAT are already starting to be used by stakeholders and have recently seen interest from a UK medical imaging company. The company was introduced to the QAT by partner NPL, with whom they have been working to develop an approach for analysing calibration data. See https://www.euramet.org/european-metrology-networks/mathmet/bugermenu/news/details?tx_news_pi1%5Baction%5D=detail&tx_news_pi1%5Bcontroller%5D=News&tx_news_pi1%5Bnews%5D=1940&cHash=4c846dd036537a29f38e2f8f40ec8f03

Wider impact

The outcomes of this project have supported the successful start of the EMN MATHMET. This project has also contributed to the long-term goals of the EMN by (i) producing the SRA for the EMN, (ii) by developing stakeholder consultation processes for the EMN MATHMET to enable it to identify the most urgent guidelines, software tools, virtual training and reference data in line with the SRA, and (iii) finally by creating a QMS for the assessment of advanced metrology software and guidance documents which ensures that the EMN MATHMET recommendations meet the highest quality levels.

The EMN has the ability to tackle the grand research challenges of modern metrology in areas such as healthcare and medical diagnostics, industrial production and quality assessment, energy and sustainability, safety and environmental monitoring. The associated EMN MATHMET, with input from this project, will also support the development of capabilities for NMI and stakeholders in the field of mathematics and statistics in metrology, thus leading to an improved European metrology research landscape.

Publications

1. Gertjan Kok, The digital transformation and novel calibration approaches. Technisches Messen, <https://doi.org/10.1515/teme-2021-0136>
2. Keith Lines, Jean-Laurent Hippolyte, Indhu George, Peter Harris, A MATHMET Quality Management System for data, software and guidelines, ACTA IMEKO, <https://doi.org/10.21014/actaimeko.v11i4.1348>
3. Gertjan Kok, Case studies for the MATHMET Quality Management System at VSL, the Dutch National Metrology Institute, ACTA IMEKO, <https://doi.org/10.21014/actaimeko.v12i2.1339>

This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

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<ol style="list-style-type: none"> 1. PTB, Germany 2. BAM, Germany 3. IMBiH, Bosnia and Herzegovina 4. INRIM, Italy 5. IPQ, Portugal 6. LGC, United Kingdom 7. LNE, France 8. NPL, United Kingdom 9. VSL, Netherlands 		