

Automatic weather stations and the quality function deployment method

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ABSTRACT: The reliability of ground-based measurements is important in a variety of meteorological areas, such as weather forecasts, air quality and climate. In order to improve this reliability, closer co-operation with the metrological community has been established. This paper looks at another possible route for improvements, based on carrying out a quality assessment of ground-based measurements using advanced quality techniques. The quality function deployment (QFD) method was adapted so as to be able to analyse the results of a survey that was conducted among meteorological community. They were asked to analyse the key performance characteristics of typical automatic weather stations (AWSs) systematically with respect to the World Meteorological Organization (WMO) classifications and requirements. The QFD is a well-known quality tool that connects customer expectations with technical functionalities or engineering characteristics. It makes it possible to prioritize the needs and quantify the results of the assessment. The answers from the survey's questionnaire were used as the input data for the QFD matrix. The findings reveal that the closest correlations are between the customer expectations or attributes and the engineering characteristics, e.g., the validation of the AWSs and the measurement methods, the regular calibration of sensors, and the implementation of automated and manual controls. From the second level of the QFD matrix, it was found that the most important technical solution serving the previously mentioned needs is related to having control over the development and upgrading of the AWSs' software and in terms of an automatic check and the transfer of data to the central database.

KEY WORDS automatic weather station; meteorology; QFD; quality

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1. Introduction

This work is being developed within the frame of the European Metrology Research Program (EMRP) joint research project 'METEOMET'. Task 3.6 of the project is focused on the software testing of automatic weather stations (AWSs) and the reliability, and consequently the quality, of AWSs. This second part is partially covered in this paper. The aim here is to present how a quality-assessment method can be used to improve the reliability of ground-based measurements. After an assessment of the needs of the end user (weather-prediction sector), the important features of the AWSs were identified. Currently, there is a need for ensuring the quality of continuous data monitoring/generation, improving the reliability and maintainability and assessing the potential risk of loss of data and false data for ground-station-based measurements. As a result, contacts were established with the end users, the meteorological services and the manufacturers. The key performance characteristics of the weather stations were systematically analysed based on a prepared questionnaire. The questionnaire matched the World Meteorological Organization (WMO) classification and requirements, WMO (2010), where a general description of the AWS properties are listed, e.g., meteorological and climatological requirements, possible types of AWS, networking,

hardware, data acquisition and processing, and software. Quality function deployment (QFD) was then adapted for the analysis of the required characteristics of the AWS based on the WMO requirements. Detailed analyses of the results obtained with the QFD method are presented in Section 3, referring to particular properties of the AWS and pointing out the important details and solutions for an optimum AWS.

2. Questionnaire

In line with the WMO classification and requirements, the performance characteristics of typical AWSs were analysed, WMO (2010). After that, a draft version of the questionnaire was prepared, which was composed of three main questions:

- what are your organizational details and the area of your meteorological work/experience;
- how does your own meteorological measuring system meet the following properties (see Figure 4);
- if you could develop your own meteorological measuring system, which properties would be important for you?

Figure 1 shows the statistical results of the questionnaire. A total of 32 full responses was received from 25 countries and from 16 different meteorological departments, which included climate, weather forecast, aviation meteorology, maintenance of the measuring equipment, data control, calibration laboratory, air quality, hydrology, management, engineering, hydro-meteo-climate service, agro-meteorology, observation,

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R&D, information and observation and seismology. The group of answers is fully representative at the European level, or even wider, since the responses in the questionnaire were also acquired from outside Europe. The answers to the questionnaire included a prioritization number for each performance characteristic, and this was the input information for the subsequent analyses.

2.1. Quality method

The analysis was carried out in order to identify potential quality tools based on the requirements of the AWS. For this reason, the most commonly used technique, i.e., the QFD, was selected as being the most appropriate one, because of the nature of the input and output data (Akao and Mazur, 2003; Han *et al.*, 2001).

The QFD method is based on the so-called House of Quality (Figure 2), which includes many rooms that are devoted to different functionalities in the quality-assessment process. The first room includes the voice of the customer, with priorities, and this is the most important part of the analysis. In the present case, these are the requirements for AWSs, which were the output from the prepared questionnaire. The second room deals with the engineering characteristics of the AWSs. In part three, connections are made between room one and room two. Room six makes possible the prioritization of needs as well as the current and desired status. Room four quantifies the quality-assessment results, and room five presents the correlations within the technical solutions.

3. QFD implementation for AWS

In the follow-up to this research, the answers to the questionnaire were analysed using the QFD quality-assessment model (Tan and Shen, 2000). According to the results of the questionnaire and the evaluation of the end-user needs, a two-matrix level of evaluation of the QFD results was designed, as shown schematically in Figure 3.

There are some key properties of the AWS that were identified by the users and, at the same time, they comply with the requirements of the WMO. The quality control of the measurements is carried out with good planning and a carefully built measurement network, including regular maintenance and calibration. In addition to monitoring the operation of the meters and the automatic measuring stations, meteorological services need to conduct regular automatic and manual control of the measured values. When planning a measurement network, the choice of the measuring location, the choice of the AWSs and the validation, including the software, are all important. It is also important to select and validate the measurement methods for each quantity and type carefully, by checking the measuring instrument for each individual quantity, including the software. The selection of the measuring point when measuring meteorological variables due to their spatial variability is extremely demanding. In rugged and overgrown terrain, it is particularly difficult to install a measuring instrument for rain and wind. In the event that an instrument is installed in a hollow, the measurements of the wind speed and velocity cannot be made correctly. In addition, when installing an instrument on a roof, the measurements of rainfall are not correct due to the exposure to the wind. An incorrect installation can lead to useless measurement results for the end users, in spite of a complete measurement system and the implementation of the entire set of requirements for the quality assurance of the measurements. In the past, automatic measuring stations mainly measured the outputs of analogue measuring instruments; however, today, their

function is to collect and aggregate the measurement results of smart meters and to communicate with the central database. The important features of measuring stations are:

- robustness;
- stability;
- functionality;
- knowledge of the operation;
- arithmetic operations carried out for the aggregate data;
- details of the implementation of automatic controls;
- hours of operation;
- transmission of data to the central database.

There are several measurement methods available to measure each variable. This means that different measurement results can be obtained, especially under extreme conditions. This is particularly true for modern, smart meters, where the core measurement method is implemented by the software. The measurement method should be selected according to the intended purpose of the measurements. Precipitation, for example, can be measured by tipping the receptacle, by weighing or by using optical methods, which count the number of droplets and measure their size through complex algorithms. Each of these methods has its own weaknesses.

In terms of construction of the measurement network, the solution for the installation of defective measuring equipment needs to be checked. Each piece of measuring equipment, as well as their interactions and common functionality, including the transmission of the measured values to a central database, is important.

To meet the requirements for the measurements, users also need to regularly maintain the measuring location and the measuring equipment. The maintenance procedures and the basic function tests, which are conducted periodically at the measuring location, are usually prescribed by the equipment manufacturer. Regular maintenance is expensive, due to the amount of manual work and the distance and accessibility of the measuring locations. This means that managers reduce the size of their networks, which can then affect the quality of the results.

The regular calibration of sensors and measuring inputs for automatic meteorological stations ensures the traceability of the measurements. The sensors should be calibrated in a calibration laboratory; however, the analogue measurement inputs of automated measuring stations are, for logistical reasons, usually only validated on site.

When carrying out meteorological measurements with modern instruments, which operate with embedded software, a major problem is software upgrading. The issuing of new software versions, which are protected by copyright and are a trade secret of the manufacturer (and therefore often poorly documented), introduces risks when performing measurements and with the accuracy of the data. Despite the similar appearance of a new version of an instrument with new software, it can have faults. This means that without verification, there could be a discontinuity in the quality assurance of the measurements. The measurer must establish control over the manufacturer's changes, usually with a new testing and validation of the instrument.

One of the biggest problems in the implementation of continuous meteorological measurements in the monitoring network is the constant operation of instruments. For this reason, it is necessary to establish automatic and manual control over their operation and to establish procedures for the shortest possible downtime with respect to the measured values. To support this requirement, the implementation of a secondary measurement instrument of the same quantity is needed. This is backup data

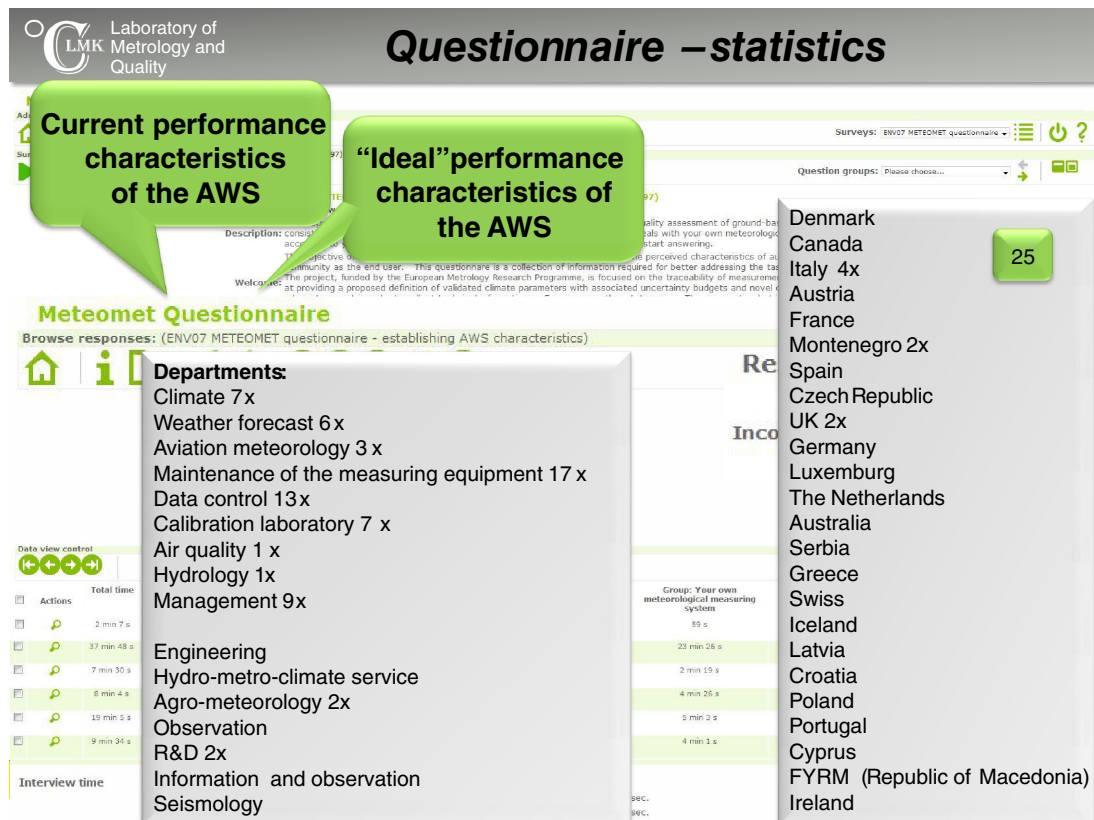


Figure 1. Statistical results of the questionnaire for QFD.

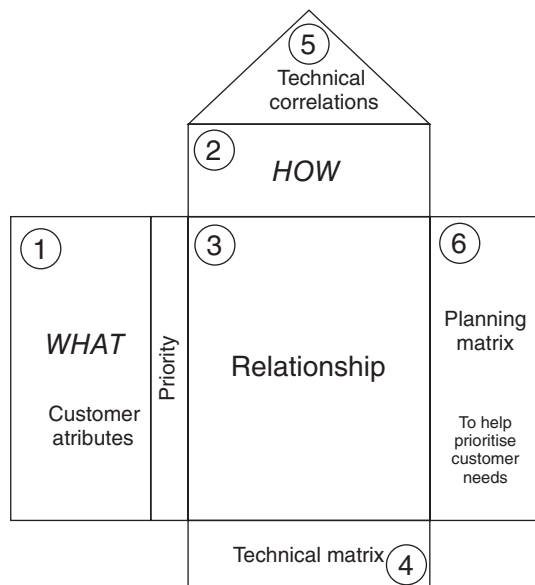


Figure 2. Example of the House of Quality.

source in the case of a failure of the main instrument. However, it can also draw attention to any drifting associated with the main instrument. The introduction of a secondary instrument, which uses a different measuring method, may supplement the information about a particular quantity in the operational measurement network during extreme events.

The last act in the measurement of meteorological data is their control. Automatic control of the program procedures is

necessary at the level of the AWS or at the level of a central database where the measured values according to carefully defined filters, such as unrealistic values, unrealistic jumps, unusual differences between neighbouring measuring stations and unrealistic values, according to the measured values of other variables, need to be checked. After the automatic control, a manual managing of data needs to be performed to fill the gaps or correct the data. It also induces emergency-service interventions in the measuring and communication equipment. Manual controls are extremely useful, but a large amount of data is difficult to handle and is expensive.

3.1. Quality matrix

When the meteorological needs are connected with the characteristics of the measuring system, which have been described above, a quality matrix can be composed, Leprevost and Mazur (2005). The main QFD House of Quality for an AWS is presented in Figure 4, and the second level is presented in Figure 5. With regard to the labels in Figure 1, those in Figure 4 and Figure 5 are marked in the same way.

The meteorological needs are marked with (1), the technical features with (2), the correlation matrix (3, 8), the calculated relative importance (4, 9), the correlation of technical features (5), the customer assessment (6) and the detailed characteristics of the automated meteorological station (7). The correlation matrix (3, 5 and 8) has evaluation signs, where Δ means a correlation power of 1, $\circ$ means a correlation power of 3 and $\ominus$ means a correlation power of 9. The value 1 means a weak correlation, and the value 9 means a strong correlation. The sign $\times$ means a negative correlation power (-1). The field (6) in Figure 4 represents the customer's assessment of the AWS's current status

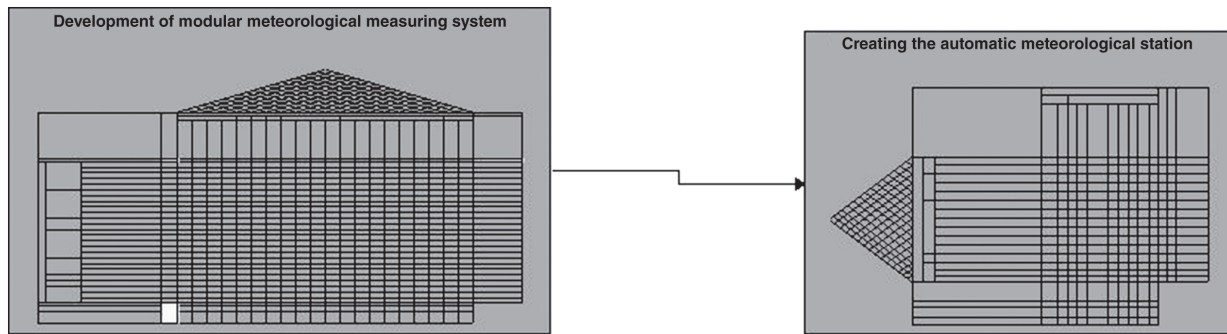


Figure 3. QFD matrix on two levels.

(●) and the needs (⊗) of the AWS, scaled from 1 to 10, where 1 means of low importance and 10 means of high importance.

The QFD matrix identifies the needs of the customer and gathers solutions. In addition, it enables a quantitative analysis to identify the most prominent segments of the AWS's properties. Furthermore, the matrix also presents standardized terminology and collects information about the AWS that is transparent in one place. Usually, the main QFD matrix presents general information about the analysed problem and its solution. More detailed results can be seen in the second or even the third or higher levels. In this case, an additional QFD matrix level was researched and presented in Figure 5. The evaluation philosophy is the same as in the main QFD matrix. Additionally, the second level presents the relative importance of both the needs and the solutions. The inputs for the second-level matrix are identified as the most prominent technical properties of the AWS and are marked with the sign ∞ (the last four columns of Technical Solutions: Part (2) in the main matrix).

4. Results of the QFD analysis

The results of the QFD matrix analyses are divided into two parts. The first part deals with the results from the main QFD matrix, which presents the highest level of problem identification. The second part presents the results of the second-level QFD matrix, dealing with more particular technical solutions that were identified as being the most important in the main matrix.

4.1. Final most prominent results of the main QFD matrix analysis

The QFD matrix in Figure 4 presents the correlations of the meteorological needs and the metrological features to fulfil these needs. The relative importance in field (4) shows the final conclusions about what features are the most important to fulfil these meteorological needs. In the process of the matrix analysis, three categories were identified, in terms of their relative importance (>500 points, between 400 and 500 points, around 300 points and <200 points).

The basic pillars of the quality assurance of the meteorological measurements (>500 points) are:

- good design and layout of the sensor network (selection and validation of the AWS, the choice of measurement methods);
- regular calibration of the measuring equipment (+ calibration of analogue inputs for the AWS);
- implementation of automated and manual controls (manual control of the measured values as a key technical solution to implement the requirements of the users).

The second set of technical solutions (400 and 500 points) is:

- type validation of the instrument (software, test instrument before installation in the network);
- inclusion of secondary gauges/meters;
- easy access to AWS software and meters.

The third part of the technical solutions (around 300 points) comprises:

- proper selection of the measuring location;
- regular maintenance of the measuring location and measuring equipment;
- control over the software upgrade of the meters;
- constant monitoring of the performance of the AWS.

The last group of technical solutions (<200 points) includes:

- efficient and controlled transfer of data to a central database;
- upgradable AWS;
- possibility to separate the operational and testing environment;
- possibility to have ongoing storage of raw data at the level of the AWS.

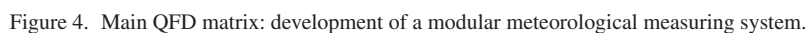
4.2. Final most prominent results of the second-level QFD matrix analysis

The QFD matrix in Figure 5 presents the correlations of the needs (which are some technical features from the main QFD matrix) and the detailed technical solutions for these needs. The relative importance in field (9) reveals the final conclusions about which solutions are the most important to fulfil these meteorological needs. In addition, field (4) presents the importance from the main QFD matrix.

The most important feature is related to the possibility for the users to do their own developing and upgrading of the AWS software and in terms of automation of the checks and the transfer of the data to the central database.

5. Conclusion

This paper introduces a quality-assessment method to the field of meteorology for an evaluation of the properties of automatic weather station (AWSs) in order to improve the reliability of ground-based measurements. After an assessment of the needs of the end users, using a questionnaire, the important features of



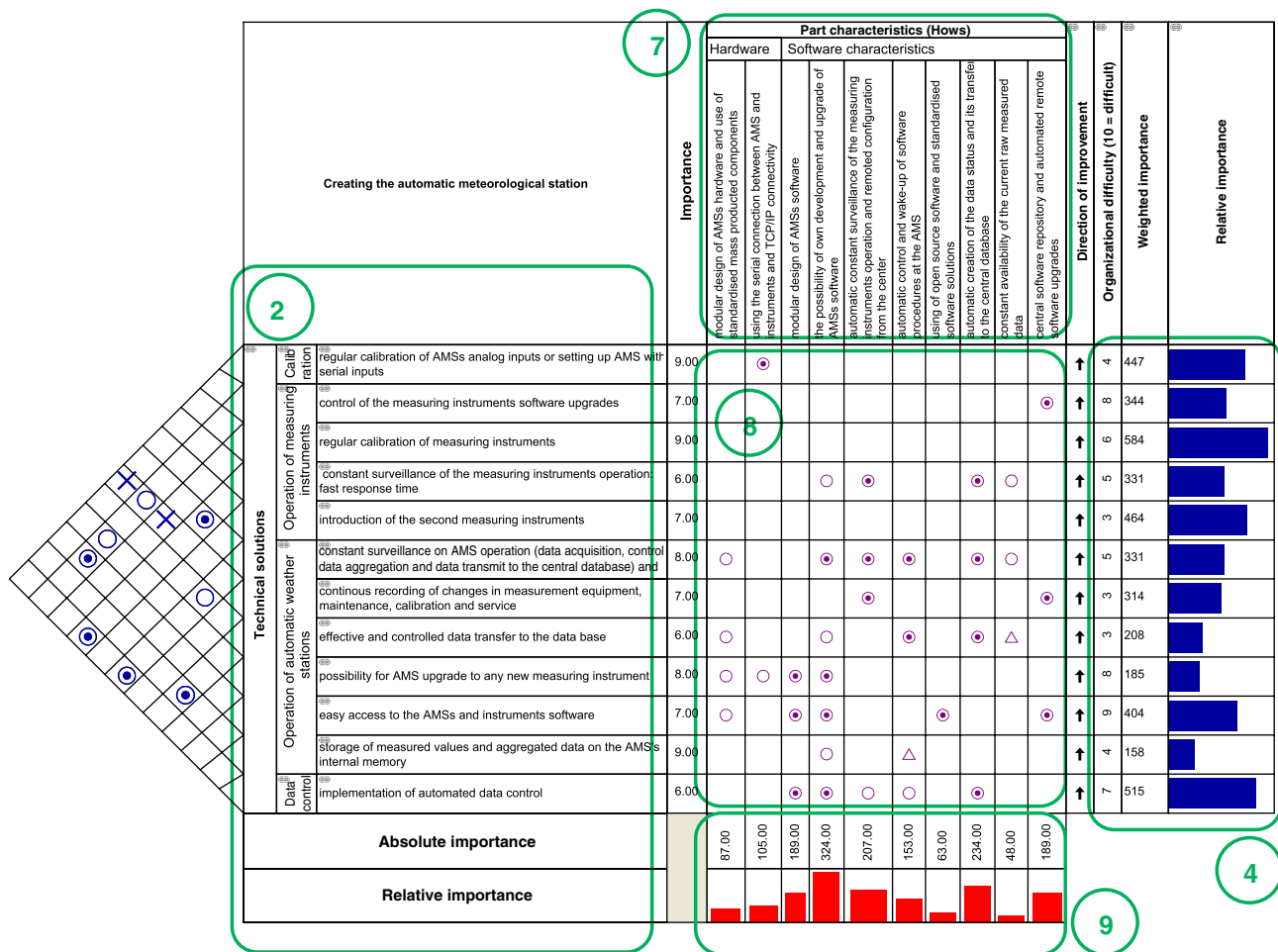


Figure 5. Second-level QFD matrix: creating the automatic meteorological station.

the AWSs were identified using the quality function deployment (QFD) method. The answers to the questionnaire, which came from 25 countries, provided representative information about the so-called 'customer need', which is the input information for the QFD. The key properties of the AWS were identified and checked to see if they comply with the requirements of the World Meteorology Organization (WMO). The QFD analyses were performed on two hierarchical levels. The main matrix identified the most prominent features of the AWS and the second level correlates these features with the technical solutions. The most important features of the AWS are connected with good layout/design of the network, traceability/calibration, automated and manual control of the data, validation of the system, inclusion of secondary gauges/meters, easy access to software and sensor information, control over software upgrades, ongoing storage of raw data and instant ability to control all the sensor and software properties (e.g., current version of software, history of changes, calibration status of sensor, sensor corrections implementation). When developing a new AWS, this information must be taken into account in order to solve the needs of the final user (meteo-services).

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