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Response Time and Intrinsic Information Quality as Criteria for the Selection of Low-Cost Sensors for Use in Mobile Weather Stations

Agnieszka Chodorek [1], Robert Ryszard Chodorek [2,*] and Paweł Sitek [1]

[1] Department of Applied Computer Science, Faculty of Electrical Engineering, Automatic Control and Computer Science, Kielce University of Technology, Al. 1000-lecia P.P. 7, 25-314 Kielce, Poland
[2] Institute of Telecommunications, Faculty of Computer Science, Electronics and Telecommunications, The AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Krakow, Poland
* Correspondence: chodorek@agh.edu.pl; Tel.: +48-12-617-4803

Abstract: Smart-city management systems use information about the environment, including the current values of weather factors. The specificity of the urban sites requires a high density of weather measurement points, which forces the use of low-cost sensors. A typical problem of devices using low-cost sensors is the lack of legalization of the sensors and the resulting inaccuracy and uncertainty of measurement, which one can attempt to solve by additional sensor calibration. In this paper, we propose a different approach to this problem, i.e., the two-stage selection of sensors, carried out on the basis of both the literature (pre-selection) and experiments (actual selection). We formulated the criteria of the sensor selection for the needs of the sources of weather information: the major one, which is the fast response time of a sensor in a cyber-physical subsystem and two minor ones, which are based on the intrinsic information quality dimensions related to measurement information. These criteria were tested by using a set of twelve weather sensors from different manufacturers. Results show that the two-stage sensor selection allows us to choose the least energy consuming (due to the major criterion) and the most accurate (due to the minor criteria) set of weather sensors, and is able to replace some methods of sensor selection reported in the literature. The proposed method is, however, more versatile and can be used to select any sensors with a response time comparable to electric ones, and for the application of low-cost sensors that are not related to weather stations.

Keywords: field experiments; mobility; quality of information; smart cities; weather sensors

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1. Introduction

The assessment of the weather condition and weather forecasting in an urbanized area is a key element of smart-city management systems. It is also a great challenge due to the specificity of the urban environment, where large differences in weather conditions occur in a relatively small area. The weather information collected in the urban canopy layer has a short-distance validity, which ranges from less than one meter to hundreds of meters [1]. Getting the current weather conditions with high accuracy and forecasting future weather conditions requires an increase in the density of weather measurement points.

Greater density of weather measurement points may be achieved by reducing the costs of weather stations through the use of low-cost sensors [2]. Such sensors are installed in, for example, smartphones, but the relatively low trustworthiness of crowdsourcing data [3] makes the usefulness of such improvised weather stations limited. The problem of the inaccuracy of environmental low-cost sensors is solved by the use of additional sensor calibration that supports factory calibration. This method was applied to both stand-alone weather sensors [4] and weather sensors being a part of integrated, weather- and pollution-sensing devices [5]. However, additional calibration increases the cost of low-cost sensors by the cost of appropriate hardware or puts an additional load on the computer system.

Another method to improve the data coming from weather sensors was presented in [6]. The quality control applied to a crowdsourced temperature data removes implausible measurements and corrects detected biases.

An alternative to the dense deployment of stationary weather stations can be mobile weather stations, in which the cyber-physical system of the weather station, including sensors, is attached to a carrier. Such mobile weather stations cover the gathering of weather information from any devices in motion, including smartphones, cars, and specialized devices built on the basis of drones. Although smartphones typically use low-cost sensors, and cars are to the contrary, solutions based on unmanned aerial vehicles (UAVs) can either use low-cost sensors (e.g., [7–9]) or not (e.g., [10–13]).

Flying weather stations that use low-cost sensors include experimental, customized, prototypical, and short-series solutions, because off-the-shelf sensors have also become the elements enabling the creation of prototype or non-standard devices, often embedded systems. Such systems use the classic Internet of Things (IoT) or its Web version—the Web of Things (WoT), which integrates smart objects with the Web [14]. A classic approach to the integration of embedded systems with the Web is sharing data through a Web page [15,16]. In this approach, Web applications do not process data from sensors. Nowadays, the increase in the performance of single-board computers (SBCs) and the development of Web browsers have made it possible to rapidly and efficiently execute the code of a downloaded Web page written as a single page application (SPA). This created both opportunities and challenges for the client-side WoT, wherein the browser is an application runtime. Opportunities included the possibility of working in mobile and/or embedded environments, and challenges include the heavy load of cyber-physical systems by SPAs and their runtimes. Our previous work has shown that the Web real-time communications (WebRTC)-based WoT application puts a heavy strain on the single-board computer on which it is running [17].

Main Contributions and Organization of This Paper

The aim of this paper is to present a method of selecting weather sensors that is oriented to solving problems arising from the use of low-cost sensors in mobile systems built as a client-side WoT. The work focuses mainly on data issues, namely on the data quality (understood in this paper as data arriving on time and with good accuracy compared to the reference data source). The proposed method was originally conceived for the needs of the WebRTC-based flying weather station presented in [18]. The main contributions of this paper are:

- the formulation of the major selection criterion is based on the response time of the sensor in a cyber-physical subsystem (not only on the sensor's fast response time); in this criterion, the sensor and its surroundings are considered as a whole, and whether or not a given sensor meets this criterion takes into account the context of the task being performed;
- the formulation of the two minor selection criteria based on the intrinsic information quality (IQ) dimensions, which deal with data accuracy; and
- conducting an exemplary selection on the basis of twelve weather sensors from different manufacturers, and then comparing the selection results with other sensor selection results described in the available literature.

The rest of this paper is organized as follows. The next section describes related work. The third section presents the selection criteria and assumptions. The fourth section describes an exemplary set of sensors and briefly discusses the experiments on which the selection was made. The fifth section shows and discusses the results of pre-selection and selection, and the sixth section compares the final results of selection with the literature. The seventh section describes use cases. The eighth section discusses the limitations of the proposed method and outlines future work. The ninth section summarizes our experiences and concludes this paper.

2. Criteria for the Sensor Selection

Many authors describing applications of low-cost weather sensors do not provide the criteria they used to choose particular sensors (e.g., Shahadat et al. [19], Adityawarman and Matondang [2], Dhungana et al. [20]). A much smaller, but still relatively large number of authors reported that they made their choice on the basis of an analysis of the literature (Madokoro et al. [7], Chiba et al. [10], Nomura et al. [11], Singh et al. [21], just to mention a few), without specifying what kind of literature it was and what literature data decided the use of one and not another sensor.

Among the criteria given by the authors of the papers, the cost of the sensor is the most frequently used one. However, only a few authors explicitly indicate the use of the cost criterion (e.g., Roldán et al. [8], Kapoor and Ferdous [22]), and only some of them explicitly indicate that this cost should be small (e.g., Kapoor and Ferdous [22], Rocha et al. [23], Math and Dharwadkar [24]). In some cases, the low sensor cost criterion is formulated implicitly, as a low-cost assumption of the entire system (e.g., Madokoro et al. [7], Shahadat et al. [19], Singh et al. [21]), or as a remark that the lower cost of weather sensors directly translates into a larger number of weather stations (Adityawarman and Matondang [2]). In many cases, the application of the low-cost criterion can be expected, based on the types of sensors used (e.g., Mestre et al. [25], Chiba et al. [10], Nomura et al. [11], Hill et al. [13], Almalki et al. [9], Kim et al. [26], Kuo et al. [27], and Ioannou et al. [28]).

Generally, the criteria for the selection of weather sensors are very different (Table 1). As an example, Mestre et al. used high resolution and stability over different atmospheric conditions [25]. The same resolution criterion (albeit without saying explicitly that it is about high resolution) was used by Roldán et al. in this paper [8]. It is worth noting that the resolution of measurements mentioned in both these papers [8,25] was considered in relation to measurands, not to the bit resolutions of sensors. The other criteria used by Roldán et al. were the range of measurements, and the weight and size of the sensor [8]. The latter criterion was used also by Hill et al. in this paper [13]. Although none of the authors cited make it clear that they mean the criterion is lightweight and small size, this is implied by default.

Table 1. Sensor selection criteria in the available literature.

Paper	Station	Sensor Selection Criteria
		Non-Low-Cost Sensors
[10,11]	mobile	analysis based on literature review
[12]	mobile	analysis based on literature review
[13]	mobile	weight, size
		Low-Cost Sensors
[25]	stationary	high resolution, stability over different weather conditions
[7]	mobile	analysis based on literature review
[19]	stationary	not specified
[2]	stationary	not specified
[21]	stationary	analysis based on literature review
[22]	stationary	low cost
[8]	mobile	weight, size, range, resolution, cost
[9]	both [1]	reliability in high temperatures, energy efficiency
[23]	stationary	low cost
[20]	portable	not specified
[26]	stationary	analysis based on literature review
[27]	stationary	analysis based on literature review
[28]	stationary	analysis based on literature review
[24]	stationary	low cost
this paper	both [1]	response time of a sensor in the cyber-physical subsystem, two defined factors of information accuracy

[1] mobile, stationary.

A noteworthy combination of sensor selection criteria was given by Almalki et al. in this paper [9]. The authors have developed a solution, useful especially in smart cities, in which data from a stationary weather station are supplemented with data from a mobile one, built by using a UAV. The selection of sensors for both of these weather stations was carried out in the same way, namely on the basis of their reliability in high temperatures (field tests were carried out in temperatures from 3 to 40 degrees Celsius) and energy efficiency. The criterion of reliability in high temperatures [9] is similar to the criterion mentioned above of stability over different atmospheric conditions [25], applied by Mestre et al.

3. Sensors Selection and Pre-Selection: Criteria and Assumptions

The sensor selection process was composed of two stages: the initial pre-selection, based on the literature, and then the actual selection, based on an experiment. The entire sensor selection process is based on criteria that define the steps of the general selection process (Figure 1) and on assumptions that match the criteria to the currently performed task.

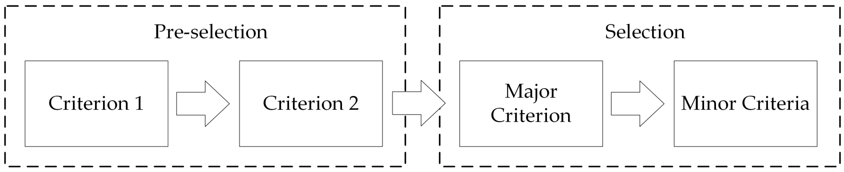

Figure 1. The general overview of sensor pre-selection and selection.

As is shown in Figure 1, the process of selection of low-cost sensors (where low cost is formally introduced as Criterion 1) starts from the site-dependent pre-selection (according to Criterion 2), which checks their ability to measure weather conditions at a given location. Pre-selected sensors are then selected according to the major criterion (Criterion 3), which checks if the sensor operating in a real system is able to make it on time in the context of a task being performed. Sensors that passed the major criterion are a subject of the selection based on the minor criteria (Criterion 4 and Criterion 5), which deal with measurement accuracy. Although the pre-selection is site-dependent and the major criterion is context-dependent, the minor criteria are reference-dependent, i.e., the accuracy of measurement is local in nature and is related to an arbitrarily selected reference weather station.

3.1. Preselection Criteria

Pre-selection reduces the number of selection experiments by finding sensors that should be excluded a priori. The aim of the proposed sensor pre-selection is to prepare a set of sensors that will be candidates for the work at the weather station. In our opinion, such sensors should satisfy two criteria, related to the cost of sensors and their potential for the performance of the assigned task.

Criterion 1. *The low cost of sensors.*

Justification. The cost of expensive sensors becomes an important part of the cost of the whole weather station. The higher the costs, the more difficult it is to gain benefits from an investment in a station. Thus, the low cost of weather monitoring systems allows one to increase the density of weather stations [2] and, as a result, it enables one to provide high-density spatio-temporal weather data. □

Criterion 2. *The site-dependent range of measurements.*

The range of measurements carried out by pre-selected sensors must be large enough to enable the sensing of weather factors at least in the range defined by maxima and minima obtained from long-term measurements carried out so far.

Justification. The range of sensors should be sufficient to carry out measurements of weather factors in any weather condition. In practice, ranges of measured quantities should be equal to (with enough margin) or greater than the maxima and minima of observed weather factors, registered for the area that will be served by a given weather station. Because of the chaotic nature of weather, which results in the self-similar character of the time series of measured weather factors, the determination of the boundaries of the ranges should be carried out on the basis of long-term measurements. □

3.2. Selection Criteria and Assumptions

The selection is made from among the candidates selected on the basis of pre-selection and is focused on the operational circumstances of the weather station, including both its ability to carry out mobile weather measurements and the two challenges presented in the first section.

3.2.1. Information Quality Aspects of Sensors Selection

Information quality, and the related term—data quality (DQ)—determines to what extent the data provided is useful at a given moment. In 1996, Richard Y. Wang and Diane M. Strong published a paper, in which they listed 20 different dimensions of IQ/DQ, grouped into four categories [29]: intrinsic, contextual, representational, and accessibility. The latter two categories do not depend on a sensor or even cyber-physical measurement subsystem, but on the system as a whole, including communication protocols. Chosen dimensions belonging to the first two categories can be used as a basis for sensor selection.

The contextual IQ/DQ requires that IQ/DQ "must be considered within the context of the task at hand" [29]. Among the five contextual dimensions (relevance, value-added, timeliness, completeness, and amount of information), the timeliness is directly related to sensors used in the measuring subsystem, and the amount of information is related indirectly (through the sample time and, if applied, oversampling). Thus, the timeliness in the context of the performed task is a basis for the formulation of the major selection criterion.

The intrinsic IQ/DQ "denotes that data have quality in their own right" [29]. All four intrinsic dimensions are either naturally related to the data coming from sensors (objectivity), or related to the results of the selection (accuracy, believability), or are related to devices taking part in the selection (reputation). The intrinsic IQ/DQ was used as a basis for the formulation of the minor selection criteria.

3.2.2. Major Criterion

The major criterion reflects the ability of a sensor to rapidly carry out weather measurements when assembled in a target cyber-physical IoT/WoT system:

Criterion 3. *The sensor's fast response time measured during the sensor's work in a target subsystem, when the subsystem's hardware–software environment and work circumstances were typical for this subsystem, is the major selection criterion.*

Justification. The major criterion answers the question: is a sensor able to carry out measurements in a given time? This time results directly from the required spatio-temporal resolution of measurements, and the resolution, in turn, results from the context in which the measurements are carried out.

The response time of the cyber-physical system, used as the major decision criterion for the sensor selection, is important especially in the case of mobile weather stations. Fast response sensors, measuring in tens of milliseconds, not seconds, give a better spatio-temporal resolution of the measurements conducted during the high-speed movement of a weather station. For example, a weather station moving at a horizontal speed of 70 km/h (e.g., a high-speed UAV) covers nearly 20 m in one second. In an urbanized environment, it is enough for the weather conditions (temperature and humidity) to change significantly in certain situations. Therefore, if we need a measurement with a spatial resolution of the order of individual meters, the sensor working at a maximum frequency of 1 Hz (response time of 1 s) will be too slow and should be rejected in the selection process. It may have many good features, but it will not be able to measure weather parameters in a given time. Moreover, this sensor may be rejected (this time due to too low a temporal resolution) even in the case of measurements carried out in established measurement points, when the mobile weather station is parking on or hovering over a measurement point for a given time. The time spent by the weather station at the measurement point must be long enough to ensure that the entire measurement is carried out when parking or hovering. This means that the time the station spends at the measurement point must be twice as long as the response time of the sensor (or several times longer than the response time of the sensor if oversampling is required). Conversely, a fast response from the sensors allows the weather monitoring system to shorten the time that the station spends parking or hovering. This, in turn, will extend the station's range, limited by the drive time (or flight time) on one battery and the total parking (or hovering) time. □

The response time is considered to be a factor of the timeliness belonging to the contextual IQ dimensions. So the assessment of whether a given electrical response time fulfills the major criterion depends on the context of the performed task. The key word in the major criterion is fast, and it is up to the person conducting the selection to define what fast means in the light of both the future tasks of the cyber-physical measuring subsystem and the mission of the whole air station. Fast is one thing for a stationary weather station and another thing for a weather station attached to a UAV traveling at 70 km/h.

Because it is typical for weather sensors to have differences between power consumption in the active measurement period and the inactive standby one, the faster a sensor's response, which shortens the active period, means a reduction in the power consumption in the case of cyclic measurements. This side effect of the short response time is important in the case of weather stations with power supplied by a battery. However, it is a side effect only and a comparison based on energy consumption should be carried out at the stage of post selection, when one chooses one sensor from among sensors that fulfill the major criterion and the minor criteria.

3.2.3. Minor Criteria

The low cost of sensors means, in practice, that mass-produced sensors (with reduced total cost per unit), that are easy to connect to the SBC and easy to install on a IoT carrier (which leads to low assembly costs), and not requiring calibration (which leads to low maintenance costs), will be preferred. Such a choice, unnecessarily and unintentionally, may reduce the accuracy of the measurement. However, modern low-cost sensors, calibrated by the manufacturers, are believed to be able to ensure getting measured data at good (or, at least, sufficient) accuracy. This means that in current weather stations, low-cost sensors are willingly used (e.g., [2,7–9,18–28]), and was the premise for formulating the two minor criteria of sensor selection.

Both minor criteria are based on the intrinsic IQ dimensions. The use of an off-the-shelf sensor entails high objectivity of the measurement information. Conversely, when it comes to accuracy and believability, these types of sensors are inherently inaccurate and unbelievable. To deal with these issues, two IQ factors were defined.

Definition 1. *The level of accuracy (LoA) reflects the difference between the sensor's measurements and data coming from the reference source: the less difference, the better intrinsic IQ.*

Justification. The less difference between a given datum from a sensor and a corresponding datum from a reference source, the better intrinsic IQ. The best intrinsic IQ would be the perfect fit between sensor data and reference source data. It is worth emphasizing that the LoA measures quality, i.e., compliance of the facts with expectations, in terms of the accuracy of the sensor's measurement. The expectations of sensor users may be different, so the selected reference sources may also be different. □

Definition 2. *Measurement information will be assessed as satisfactory in terms of believability (i.e., believable at a satisfactory level), if it was within the level of satisfaction (LoS).*

Definition 3. *The binary level of satisfaction (BLoS) determines whether the measurement information is considered sufficiently believable or not.*

Justification. The BLoS defines the framework within which information is considered to be satisfactorily believable. Measurements that exceed the BLoS are considered as non-satisfactory (in terms of believability), so the sensor should be considered as non-satisfactorily believable. □

Although the lack of legalization of sensors means that measurements are considered to be inaccurate and uncertain, persons who deal with low-cost sensors are usually not interested in passing the full legalization process or, because accuracy of low-cost sensors is far from being perfect, passing the legalization process would be difficult or even impossible. Defined below the minor criteria of sensor selection allows for a rough comparison of the extent to which the measurements from a given sensor are consistent with the measurements made by a weather station arbitrarily named as the reference station.

Criterion 4. *The Level of Accuracy is the first minor criterion.*

Justification. This criterion deals with the accuracy of the IQ dimension and shows the deviation of a measurement (single or average) from the corresponding reference source measurement. It answers the question of how accurate the measurement data from a sensor is (in relation to a given source). The LoA is not a measurement of error in the strict sense, including systematic error, although a numerical measure of LoA may be expressed by a measurement error. □

Criterion 5. *The BLoS is the second minor criterion.*

Justification. The BLoS, which is the basis of this criterion, deals with the believability IQ criterion and answers the question of whether the measurement data coming from a sensor are believable. The BLoS assumes that the assessment of a given measurement on the LoS is binary—if the measurement is outside the LoS, it is considered satisfactory. Gross errors can always happen, but if the measurements are too often unsatisfactory, this data source should be considered unbelievable and the sensor should be rejected during the selection. □

The last, fourth intrinsic IQ dimension is the reputation. The low-cost sensors have, generally, a dubious reputation (as sources of measurements of unknown accuracy), but the proposed selection method means that the reputation of particular systems that use low-cost sensors may reach a level similar to the level of the weather station selected as the reference. This leads to the obvious, intuitively understandable conclusion that only weather stations with an established, good reputation should be used as reference ones.

3.3. Assumptions

The fulfilling of the minor criteria (Criterion 4 and Criterion 5) must be checked experimentally. The fulfilling of major criterion (Criterion 3) may be checked on the basis of a technical literature review. It is sufficient if the weather stations are built on classic, well-established, and well-researched solutions, and they work with polling periods long enough to assure that all sensors will be ready to make measurements (including oversampling).

However, if the response time of a sensor is close to the polling periods, an analysis based on a review of the technical literature may not be sufficient. Sometimes manufacturers or vendors of low-cost sensors list the minimum response time as the nominal one. Moreover, in the case of weather stations based on a client-side Web of Things, the measuring application and its runtime environment puts a heavy load on the single-board computer on which they are run. This may have an impact on the response time of the cyber-physical measurement system observed as a whole. Our previous experiences, described in this paper [17], show that response times measured when temperature and humidity sensors operate on board the air station can differ from the nominal ones by from 10% to 30% (10–25% on average). In the case of one of the tested sensors, even a 75% difference was observed between maximum measured temperature and the one given in the sensor's specification (44% on average). For applications working with polling times close to the sensors' response times, such large differences may affect the selection process.

As a result, the following assumption was made.

Assumption 1. *The fulfilling of the selection criterion should be checked experimentally.*

If the sensor is to be operated under a wide range of weather conditions, the accuracy of the sensor over different weather conditions should be checked (assumption adopted from [25]). This also applies to the response time—at least the stability at different temperatures should be checked. The stability over different weather conditions should be checked experimentally.

Assumption 2. *The fulfilling of the selection criterion should be checked in different weather conditions.*

As the method is intended for the selection of low-cost sensors, the cost of sensors should not be increased by the need to purchase or rent expensive equipment (e.g., a climatic chamber). If preliminary experiments using limited but available on-site resources did not show the sensitivity of the sensors to different weather conditions, and the tests using other equipment were too expensive, further research may be dispensed with and/or Assumption 2 may be omitted in subsequent tests.

Assumptions 1 and 2 should be used in the case of the checking of the fulfillment of the major criterion, which deals with sensors' response times, and must be used for the checking of the fulfillment of the minor criteria, which deals with the measurement accuracy.

3.4. Measures of the Level of Accuracy and the LoS

To use the minor criteria, one must define numerical measures of the two information quality factors, the LoA and the LoS, introduced in the previous section. These measures should reflect the expectations of the users of a system, in which the sensors will be installed.

For the purposes of the selection presented in this article, we define the numerical measure of the LoA as the worst-case (the greatest positive one or the smallest negative one) mean deviation from the measurement information coming from the reference weather station.

Definition 4. *The measure of the LoA is the worst-case mean difference between the result of a measurement and corresponding information from a reference source, collected in various weather conditions:*

$$|LoA| = \max_{j=1\ldots M} |m_j|, \tag{1}$$

where M is the total number of the measurement series, carried out in different weather conditions, j is the j-th series of measurements, and m_j is the mean value that results from an N_j number of measurements of the same measurand carried out under the same weather conditions, minus the value of the measurand coming from the reference source:

$$m_j = \frac{1}{N_j} \sum_{i=1}^{N_j} [s_{i,j} - r(i,j)], \tag{2}$$

where s_i, j is the i-th measurement of a measurand belonging to j-th series of measurements, and $r(i, j)$ is the value of the same measurand valid when the $s_{i,j}$ measurement was carried out.

Justification. It is believed that low-cost sensors suffer not only from poor accuracy, but also from measurement instability under various weather conditions. The literature indicates the need to make a selection either directly on the basis of stability over different weather conditions [20] or on the basis of reliability at high temperatures [27]. Taking the above into account, measurements cannot be averaged over all series of measurements, but over each series separately. For determining the LoA, the mean deviation of the most inaccurate series from the reference source is selected. □

For the purposes of the selection presented in this article, we propose to use the error bound of the reference weather station as the measure of the LoS.

Definition 5. *The LoS is the tolerance range of a reference weather station.*

Justification. Delivered measurement information will be assessed as satisfactory in terms of believability if it was within the tolerance range of the reference weather station. Measurements that exceed the error bound of the reference weather station are considered as non-satisfactory. □

3.5. Summary

The process of selecting sensors for the needs of mobile weather stations was intended to answer two questions:

- Is the sensor able to perform the desired measurement?
- If the answer to the previous question is "yes", can the sensor measure with a satisfactory accuracy?

Figure 2 shows a block diagram of the overall sensor selection process. At the very beginning, the set of sensors S is a subject of selection, and the set of excluded sensors F is empty. The set F is a subset of the set S. Sensors that have not passed a given selection step are added to the set F. In the next step, only those sensors from the S set that do not currently belong to the F set (the $S \setminus F$ set, i.e., sensors that have passed all the selection steps so far) take part.

The selection process is structurally divided into two parts, pre-selection and the actual selection (Figures 1 and 2). Pre-selection begins with a filter that excludes non-low-cost sensors from the set of sensors S (Criterion 1). The next step (Criterion 2) answers the question: Does the sensor have a sufficient measuring range to be able to carry out environmental measurements in a given location? This is checked on the basis of a technical literature review.

All low-cost sensors able to carry out environmental measurements in a given location are the subject of an actual selection in which it is checked whether the sensors meet the major criterion and two minor ones. The major criterion (Criterion 3) checks whether the weather-monitoring system with the installed sensor can cope with the time constraints introduced by the monitoring task being performed. Time constraints result from the spatio-temporal resolution of measurements and other operating parameters, the most important of which is the speed of movement of the mobile weather station. The fulfillment of the major criterion can be checked on the basis of a literature review. Nevertheless, the authors recommend that in the event that the response time is approaching the threshold and when the SBC is heavily loaded (as is the case with Web of Things systems), the check should be take place by way of an experiment.

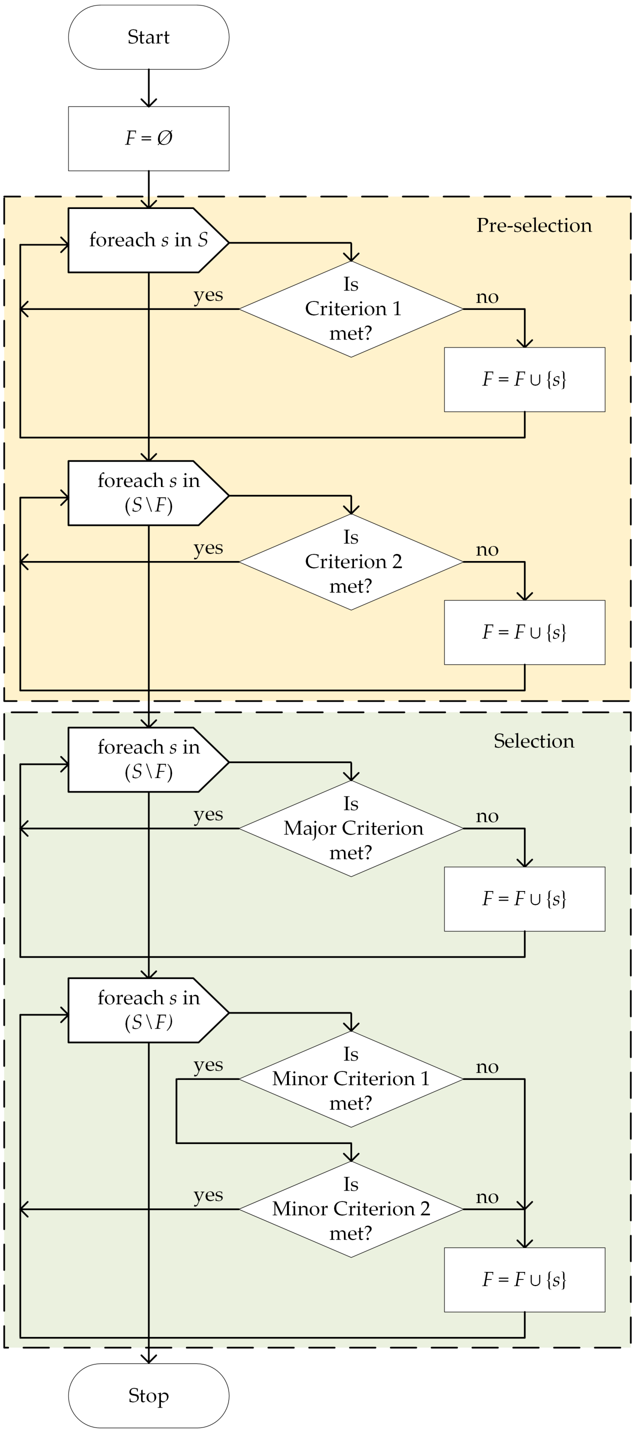

Figure 2. The flow diagram of sensor pre-selection and actual selection. S, set of sensors, F, set of sensors that have not passed all the selection steps so far, $(S \setminus F)$, set of sensors that have passed all the selection steps so far.

The sensors that have passed both the pre-selection and the selection with the use of the major criterion are then selected with the use of two minor criteria. These criteria are designed to check whether a given sensor is able to measure weather factors with a satisfactory accuracy. The measurement accuracy is not absolute here, but is determined on the basis of the measurement results of the reference station. This requires a series of measurements to be made in conditions as close as possible to those of the reference station. As the verification of the minor criteria (Criterion 4 and Criterion 5 or Minor Criterion 1 and Minor Criterion 2, respectively) is performed after a series of experiments, both criteria are tested together in the same cycle (Figure 2).

The selection process can be decisive, i.e., after its completion the $S \setminus F$ set has a cardinality of 1. Most often, however, it will not be conclusive, i.e., $card(S \setminus F) \neq 1$. Then, if $S \setminus F = \emptyset$, no sensor meeting the selection criteria was found. Moreover, if $card(S\ F) > 1$, many sensors meeting the selection criteria were found. In the latter case, all sensors that pass the selection may be used in the weather station or, in order to select a single sensor, post-selection should be performed. The post-selection may be achieved through someone's arbitrary decision, through a draw, or it may be based on the analysis of features of the selected sensors. Such features may be directly related to the selection criteria (e.g., the shortest response time, the best accuracy), may be related to them indirectly (e.g., lowest energy consumption, indirectly related to short response time), or may not be relevant to them (e.g., streamlined shape of the sensor board).

4. Experiments

Experiments aimed at collecting data for the purposes of the selection of sensors for the flying weather station were carried out at the campus of the AGH University of Science and Technology in Krakow (Poland). In experiments, twelve sensors were used (Table 2): eight temperature and humidity sensors, two UV index sensors, one air pressure and temperature sensor, and one air pressure, temperature, and humidity sensor. The considered sensors were produced by different manufacturers. They covered a wide spectrum of response times (from milliseconds to seconds) and applications (from heating, ventilation, and air conditioning systems, through weather stations, to smart wearable devices, such as smartwatches, smartphones, and smartbands).

Table 2. Sensors that were the subject of selection.

Sensor Type	Manufacturer	Measured Factors
AM2320	Adafruit	temperature and humidity
BMP280	Bosch	temperature and atmospheric pressure
BME280	Bosch	temperature, humidity, and atmospheric pressure
DHT11	Adafruit	temperature and humidity
DHT22	Adafruit	temperature and humidity
HTU21D	Measurement	temperature and humidity
HDC1080	Texas Instruments	temperature and humidity
SHT30	Sensirion	temperature and humidity
SHT35	Sensirion	temperature and humidity
SI1145	Silicon Laboratories	infrared proximity, UV index, and ambient light
Si7021	Silicon Laboratories	temperature and humidity
VEML6070	Vishay Semiconductors	UV radiation

As the target system, in which the selected sensors will be installed, the framework intended for the fast prototyping of specialized flying monitoring systems, presented in our previous paper [17], was used. The SBC used in this system was the Raspberry Pi 4 Model B. It was working under the control of the Raspbian operating system (OS) (a modification of the Debian distribution of the Linux OS). On the SBC, the Chromium browser working in headless mode was run, which was the runtime environment for the WebRTC application of the IoT broker, written as the SPA using hypertext markup language version 5 (HTML5) and JavaScript languages.

As the reference weather station, the SBS-WS-400 was used. This station has a good reputation as it is widely believed to be a reliable source of weather information. The chosen technical parameters of the SBS-WS-400 are presented in Table 3. The weather station is mounted on a mast on the roof of the Institute of Telecommunications of the AGH University (Figure 3). Differences between data coming from the WebRTC-based IoT and from the SBS-WS-400 weather station were used to draw conclusions about the quality of measurement information and, as a result, about the suitability of a given sensor for use in the target system.

Figure 3. The SBS-WS-400 weather station mounted at the roof of the Institute of Telecommunications, selected as the reference one.

Table 3. Chosen parameters of the SBS-WS-400 weather station, selected as the reference one.

Measurand	Measurement Range	Measurement Accuracy
Temperature	−40 °C to 60 °C	±1 °C
Humidity	10% to 99%	±5%
Atmospheric pressure	300 hPa to 1100 hPa	±3 hPa (700 hPa to 1100 hPa)

To check how the major criterion was fulfilled, response time tests were conducted. The methodology of these tests was the same as was used in the paper [17], in the response time tests of the temperature and humidity sensors. Despite the different aims of the two experiments, the same methodology meant there was no need to re-test the temperature and humidity sensors. As a result, only tests of the response time of atmospheric pressure measurements and tests of the UV Index sensors were carried out. Sensors were cyclicly pooled by the SPA running at the SBC, their response times were recorded, and then averaged over 100 times. To meet Assumption 1, the tests were carried out in an air conditioned room, and during experiments the air condition settings were changed.

To check whether the sensors complied with the minor criteria, a series of tests were performed. Because the roof of the building of the Institute of Telecommunications is equipped with a platform for experiments, the WebRTC-based IoT was placed close to the sensors of the SBS-WS-400 weather station. Each test lasted a few minutes, during which time each 0.5 s a measurement of the weather factors were carried out. The experiments were conducted over four months, from late January to early June, which meant that they were repeated in different weather conditions. As a result, according to the results of measurements carried out using the SBS-WS-400, during the four-month tests the range of measured temperatures was from 4.9 °C to 25.2 °C, humidities from 41% to 89%, atmospheric pressures from 979.9 hPa to 998.4 hPa, and UV Indexes from 0 to 7.

5. Results

This section includes results of preselection according to Criteria 1 and 2, selection according to Criteria from 3 to 5, and post-selection, applied if needed. Experiments for selection purposes were conducted in Krakow, and pre-selection was carried out on the basis of meteorological data from this city and the specifications of particular sensors. The final results of the selection process are summarized in the last subsection.

5.1. Pre-Selection

The sensor selection, based on experimentation, follows the sensor pre-selection based on the cost of the sensors and the technical literature review. The aim of this sensor pre-selection is to choose a set of low-cost sensors that are able to take weather measurements to the extent known from site-dependent historical data. During the pre-selection, the maxima and minima of weather factors measured over the whole of the 20th century were taken as the basis for the determination of the minimal boundaries of the ranges of weather sensors.

In Krakow, atmospheric pressure has been accurately measured since 1792, including throughout the whole of the 20th century, at the same measuring point inside the Śniadecki College building of the Jagiellonian University, 220 m above sea level and not reduced to sea level [30]. The minimum atmospheric pressure recorded in Krakow in the 20th century was 978.2 hPa (1915), and the maximum one was 1004.5 hPa (1959) [30]. These values are inside of the range of both atmospheric pressure sensors listed in Table 4, so they both passed the pre-selection. Low-cost atmospheric pressure sensors that pass the pre-selection were able to perform measurements from 300 hPa to 1100 hPa.

Table 4. Pre-selection of atmospheric pressure sensors.

Sensor Type	Range [1]	Resolution [1]	Accuracy [1]	Accuracy [2]	Pre-Selection
BMP280	300 hPa to 1100 hPa	0.0016 hPa	1 hPa	0.01 hPa	passed
BME280	300 hPa to 1100 hPa	0.0016 hPa	1 hPa	0.01 hPa	passed

[1] absolute, [2] relative.

Temperature measurements also were carried out in Krakow from 1792, and in the 20th century the minimum registered air temperature was −32.7 (1929), and the maximum one was 37.4 (1921) [31]. Thus, the minimum value measured by temperature sensors that pass the pre-selection was −40 °C, and the maximum one was at least +80 °C. This condition was met by 9 out of 10 sensors listed in Table 5. The popular and often used DHT11 low-cost temperature and humidity sensor was not able to pass pre-selection for the weather station operating in Krakow, because the temperature sensor does not offer a suitable operating range. The old series of DHT11 were able to measure ambient temperatures from 0 °C to +50 °C (instead of at least from −33 °C). Although DHT11 specifications indicate the operating range of new series is from −20 °C to +60 °C, it is still insufficient, because temperatures below −20 °C are not uncommon in winters in Krakow.

Table 5. Pre-selection of temperature sensors.

Sensor Type	Range	Resolution	Accuracy	Pre-Selection
AM2320	−40 °C to +80 °C	0.1 °C	±0.5 °C	passed
BMP280	−40 °C to +85 °C	0.01 °C	±0.5 °C	passed
BME280	−40 °C to +85 °C	0.01 °C	±0.5 °C	passed
DHT11 [1]	0 °C to +50 °C	1 °C	±2 °C	failed
DHT11 [2]	−20 °C to +60 °C	0.1 °C	±2 °C	failed
DHT22	−40 °C to +80 °C	0.1 °C	±0.5 °C	passed
HTU21D	−40 °C to +125 °C	0.01 °C	±0.3 °C	passed
HDC1080	−40 °C to +125 °C	0.1 °C	±0.2 °C	passed
SHT30	−40 °C to +125 °C	0.01 °C	±0.2 °C	passed
SHT35	−40 °C to +125 °C	0.01 °C	±0.1 °C	passed
Si7021	−40 °C to +125 °C	0.01 °C	±0.4 °C	passed

[1] old series, [2] new series.

Humidity measurements have been performed in Krakow since 1830 [32]. The lowest recorded relative humidity was 23% (1906), and the maximum one was 100% (the state of saturation, which was achieved from time to time) [32]. Humidity sensors that pass pre-selection were able to measure relative humidity over the entire range, from 0 to 100% (Table 6). This condition was met by almost all sensors except DHT11, i.e., the same sensor that was excluded from the further temperature measurements. The operating range of the old series of DHT11 is 20% to 90%, and also in this case the specification of the new series of this sensor gives a wider operating range (5% to 95%) when compared to the old ones. However, it is still not enough to measure humidity in Krakow, which is in a valley, on the banks of the greatest Polish river, where relative humidity sometimes reaches 100%.

Table 6. Pre-selection of relative humidity sensors.

Sensor Type	Range	Resolution	Accuracy	Pre-Selection
AM2320	0% to 99.9%	0.1%	±3%	passed
BME280	0% to 100%	0.008%	±3%	passed
DHT11 [1]	20% to 90%	1%	±5%	failed
DHT11 [2]	5% to 95%	1%	±5%	failed
DHT22	0% to 100%	0.1%	±2%	passed
HTU21D	0% to 100%	0.04%	±2%	passed
HDC1080	0% to 100%	0.1%	±2%	passed
SHT30	0% to 100%	0.01%	±2%	passed
SHT35	0% to 100%	0.01%	±1.5%	passed
Si7021	0% to 100%	0.025%	±3%	passed

[1] old series, [2] new series.

Only two decades have passed since the World Health Organization (WHO) introduced the global solar ultraviolet (UV) index [33]. Thus, long-term measurements in the 20th century were, for obvious reasons, impossible. As a result, we decided not to apply Criterion 2 for pre-selection of UV index sensors with the use of other historical data. We limit our considerations to Criterion 1 only, which is met by both considered sensors. Nevertheless, ranges of considered UV index sensors are high. Although the SI1145 documentation lacks precise data on the scope of work, the graph presented here shows the range of the UV index from 0 to about 10. For VEML6070, the documentation only gives a maximum 5 μW/cm^2 (UVA) power of 328 mW/cm^2, which when converted gives a UV index of approximately 11. It is therefore safe to assume that both sensors are able to measure the UV index in the range of 0 to at least 9.

5.2. Selection

Sensors that passed the pre-selection were the subject of an actual selection, based on Criterion 4 and Criterion 5. This section presents three examples of selections, which differ in the number of sensors participating in the selection and the results obtained. They are: selection carried out on a small set of atmospheric pressure sensors (selection criteria were met by all sensors, there is a clear result of selection), selection carried out on a larger set of air temperature and relative humidity sensors (selection criteria were not met by some sensors, there is a clear result of selection), and selection that was carried out on a small set of UV index sensors (selection criteria were met by all sensors, no decisive results of selection).

If the sensor selection experiments do not bring decisive results, two decisions are possible. The first one is that all sensors that pass the selection will be used in the weather station. The second one is that post-selection will be performed. The post-selection may be based on the analysis of features of the selected sensors to find the most useful one (or ones). But just as well, the determination of the sensor can be done randomly or it can be an arbitrary decision which sensor will be used in the weather station.

5.2.1. Atmospheric Pressure Sensors

As was presented in previous section, both considered atmospheric pressure sensors, namely the Bosch Sensortec BMP280 and the Bosch Sensortec BME280, passed the pre-selection. These sensors were then laboratory-tested in the flying weather station in terms of response time (the electrical one).

The results collected in Table 7 show that the response times achieved by the BMP280 and the BME280 being a part of the fully operational flying weather station were usually slightly slower (maximum 0.6 ms slower, on average 0.3 to 0.4 millisecond slower) than the nominal ones included in the specification of each sensor. During laboratory tests, the Bosch Sensortec BME280 was not able to achieve its nominal response time, and its mean response time was 0.1 ms slower than the one determined for the Bosch Sensortec BMP280. Nonetheless, such a small difference in response time, as described above, cannot be considered as decisive for weather monitoring.

Table 7. Comparison of response time (in ms) of atmospheric pressure sensors.

Sensor Type	Measurements			Nominal	Major Criterion
	Min	Max	Mean		
BMP280	6.4 ms	7 ms	6.7 ± 0.1 ms	6.4 ms	passed
BME280	6.5 ms	7 ms	6.8 ± 0.1 ms	6.4 ms	passed

Because during field pre-tests both analyzed sensors met the minor criteria (Table 8), the final decision was taken on the basis of the additional capabilities of the atmospheric pressure sensors. The Bosch Sensortec BMP280 offers a limited capability relative to the Bosch Sensortec BME280 (pressure and temperature measurements vs. pressure, temperature, and humidity). As a result, the BME280 was selected to be one of the input devices of the flying weather station.

Table 8. Comparison of worst-case differences between data from atmospheric pressure sensors and data from the reference weather station.

Sensor Type	LoA	Criterion 4	Max	Criterion 5	Minor Criteria
BME280	0.52 hPa	passed	1.3 hPa	passed	passed
BMP280	0.51 hPa	passed	1.2 hPa	passed	passed

5.2.2. Temperature and Humidity Sensors

The classic problem-solving principle, formulated by the 17th-Century philosopher Johannes Clauberg states "entities should not be multiplied beyond necessity" ("*entia non sunt multiplicanda praeter necessitatem*"). Thus, the typical sensor's selection presented in the literature assumes that the use of the two-in-one and the three-in-one weather sensor (usually, temperature and humidity in one, and atmospheric pressure, temperature, and humidity in the other) entails the necessity of the use of this sensor for all possible measurements. According to this common practice, the natural candidate for the temperature and humidity sensor of the weather station was the Bosch Sensortec BME280, chosen in the previous subsection for atmospheric pressure measurements.

The ability to fulfill the major criterion by particular temperature and humidity sensors is summarized in Table 9. It was checked on the basis of the results of experiments presented in the article [17], which include tests of the UAV-based and WebRTC-based framework co-operating with the same sets of popular low-cost sensors. However, when compared to other fast response sensors, with the mean response time of 12–13 ms the BME280 turned out to be one of the three slowest temperature sensors (besides the Bosch Sensortec BMP280 and Measurement HTU21D), and the slowest humidity sensor. Nonetheless, it still met the major criterion for sensor selection (response time was small enough to enable proper work of this sensor in the target monitoring system), and its response time was two orders of magnitude smaller than the response times of the popular Aosong DHT22, or Aosong AM2320 sensors, which are used, among other things, in weather stations, and which do not fulfill the major criterion (Table 9).

Table 9. Comparison of the response time of temperature and humidity sensors (on the basis of [17]).

Sensor Type	Temperature					Humidity				
	Time				Major Criterion	Time				Major Criterion
	Min	Max	Mean	Nominal		Min	Max	Mean	Nominal	
AM2320	2.1 s	2.3 s	2.2 s	2.0 s	failed	2.1 s	2.4 s	2.2 s	2.0 s	failed
BME280	11.5 ms	14 ms	12 ms	11.5 ms	passed	12.5 ms	16 ms	13 ms	12.5 ms	passed
BMP280	9.7 ms	14 ms	12 ms	9.7 ms	passed	–	–	–	–	–
DHT22	2.1 s	2.4 s	2.2 s	2.0 s	failed	2.1 s	2.4 s	2.2 s	2.0 s	failed
HDC1080	3.65 ms	4.1 ms	4.0m s	3.65 ms	passed	3.85 ms	4.2 ms	4.1 ms	3.85 ms	passed
HTU21D	11 ms	14 ms	12 ms	11 ms	passed	4 ms	6 ms	5 ms	4 ms	passed
SHT30	4.5 ms	6.5 ms	5 ms	4.5 ms	passed	4.6 ms	6.5 ms	5.1 ms	4.5 ms	passed
SHT35	4.8 ms	6.4 ms	5.1 ms	4.5 ms	passed	4.8 ms	6.5 ms	5.2 ms	4.5 ms	passed
SI7021	2.4 ms	4.2 ms	3.5 ms	2.4 ms	passed	3.7 ms	5 ms	4.1 ms	3.7 ms	passed

In the second stage of selection, the Bosch Sensortec BME280 achieved the worst quality of temperature information of all tested temperature sensors. It often happened that it was the worst of all tested temperature sensors (Table 10). It frequently happened that the error bound of the temperature measurements of the reference station (±1 °C) was exceeded, which made the measurement non-satisfactory in terms of believability. This meant that the Bosch Sensortec BME280 did not pass the selection in terms of temperature, so it cannot be used as the primary sensor and should not be used as the secondary one for temperature measurements for weather station purposes.

Table 10. Comparison of worst-case differences between data from temperature and humidity sensors and data from the reference weather station.

Sensor Type	Temperature					Humidity				
	LoA	C4 [1]	Max	C5 [2]	Minor [3]	LoA	C4 [1]	Max	C5 [2]	Minor [3]
BME280	1.24 °C	failed	1.26 °C	failed	failed	−1.95%	passed	−2.1%	passed	passed
BMP280	0.89 °C	passed	0.93 °C	passed	passed	–	–	–	–	–
HTU21D	0.57 °C	passed	0.58 °C	passed	passed	−0.84%	passed	−0.91%	passed	passed
HDC1080	0.49 °C	passed	0.56 °C	passed	passed	13.28%	failed	13.42%	failed	failed
SHT30	0.36 °C	passed	0.39 °C	passed	passed	4.79%	passed	4.89%	passed	passed
SHT35	0.39 °C	passed	0.42 °C	passed	passed	6.85%	failed	6.96%	failed	failed
Si7021	0.28 °C	passed	0.31 °C	passed	passed	6.88%	failed	6.97%	failed	failed

[1] Criterion 4, [2] Criterion 5, [3] Minor Criteria.

The Bosch Sensortec BME280 was one of the three sensors that met the minor criteria during humidity measurements and, as a result, passed the selection in terms of the humidity measurement. The other ones were the Sensirion SHT30, which achieved the worst accuracy of these three sensors, and the Measurement HTU21D, which achieved the best accuracy of all tested humidity sensors (Table 10). Although both SHT30 and HTU21D have passed minor criteria in terms of temperature (Table 10), the most accurate temperature sensor turned out to be the Silicon Laboratories Si7021. It, in turn, failed its selection as a humidity sensor. Therefore, if the principle of "entities should not be multiplied beyond necessity" was disregarded, or if, in the light of the results summarized in Table 9, it is necessary to use two different sensors, the Si7021 and the HTU21D would be selected as a result of the selection. Otherwise, a choice must be made between Sensirion SHT30 and Measurement HTU21D.

The SHT30 better reflects the temperature measurements made by the reference station than the HTU21D. In the case of the humidity measurement, the opposite is true. In other words, the SHT30 achieved a greater LoA in measuring temperature, and the HTU21D in measuring humidity. Because the LoA of the SHT30 in humidity is close to the LoS, and the

LoA of the HTU21D in temperature is in the middle between the perfect fit and the LoS, in the post-selection the HTU21D was designated as the temperature and humidity sensor.

5.2.3. UV Index Sensors

The selection of the UV index sensors was carried out by using the Silicon Laboratories SI1145 and the Vishay Semiconductors VEML6070. Generally, the VEML6070 is less convenient to use as a UVI sensor. As is shown in Table 11, the VEML6070 has a relatively slow response time—an order of magnitude slower than was measured for the SI1145. Bearing in mind the fact that this slow response time is mainly influenced by the long integration time (the standard integration time is 125 ms), and a longer integration time usually goes hand in hand with higher accuracy, this cannot be considered a disadvantage. Especially considering the longer integration time is in the order of tenths of a second, not seconds. Consequently, despite the relatively long response time of the VEML6070, both sensors fulfill the major criterion.

Table 11. Comparison of response time (in ms) of UV index sensors.

Sensor Type	Measurements			Nominal	Major Criterion
	Min	Max	Mean		
SI1145	18 ms	21 ms	20 ms	not available	passed
VEML6070	126 ms	129 ms	127 ms	not available	passed

During field experiments, both sensors achieved comparable worst-case results (Table 12). At this point, it is worth mentioning that the manual of the SBS-WS-400 weather station [34], used as the reference weather station, does not offer precise accuracy of the UV index measurement. Due to the lack of precise data, we have assumed that for selection purposes the measurement accuracy is half a gradation, i.e., 0.5. On this basis, we concluded that both sensors fulfilled the minor criteria.

Table 12. Comparison of worst-case differences between data from UV index sensors and data from the reference weather station.

Sensor Type	LoA	Criterion 4	Max	Criterion 5	Minor Criteria
SI1145	0.02	passed	0.14	passed	passed
VEML6070	0.05	passed	0.18	passed	passed

The analyses shown in Table 12 are necessarily very coarse and did not produce a conclusive result. The decision should therefore be made at the post-selection stage. However, both the Silicon Laboratories SI1145 and the Vishay Semiconductors VEML6070 have good ambient temperature compensation (from −40 °C to +85 °C). They are both equipped with internal integration circuits and low-pass filters. Because the major criterion, and the two minor criteria showed that there is no clear advantage of either sensor, nor any clear contraindication, both of these sensors were found to be equally useful for a weather station. As a result, one should now choose one of them in any way, for example by drawing lots, or by installing both sensors in the target weather station and continuing their tests.

5.3. Discussion

The low-cost atmospheric pressure sensors market is currently dominated by a very successful design by one of the manufacturers. As a result, the solutions listed in Table 1 use only three types of low-cost air pressure sensors. They are the Bosch BMP180 [19,20,22,24,28], the Bosch BMP280 [23] and the Bosch BME280 [2,7,9,22]. The BMP180 is the older version of the BMP280. The use of the old version, which currently has an end of life (EOL) status, instead of the new one, was usually explained by a search for easily available and cheap components.

Almost the same set of sensors (with the exception of the BMP180, which has lost its value as a budget solution in Europe: the currently available BMP180s are more expensive than the newer BMP280s) were considered as atmospheric pressure sensors for weather station purposes. The pre-selection was passed by both BMP280 and BME280. The BMP280 and the BME280 also passed the selection. The three-in-one (air pressure, temperature, and humidity) BME280 sensor was chosen in post-selection, as potentially more useful than the two-in-one (air pressure and temperature) BMP280. However, in light of the selection criteria, the decision to use the BMP280 was equally legitimate.

The same situation concerning the lack of a variety of solutions, albeit for a different reason, occurred in the case of the UV Index sensors. Most of the weather stations known from the literature do not yet implement the UV index measurement. In the case of the solutions listed in Table 1 only two such sensors were used. They are the UV index sensor being a part of the multi-sensor Xiaomi Plant Monitor device [27] and the Silicon Laboratories SI1145 [7]. The PlantMonitor does not directly measure the UV index but is said to have a wide range and is accurate. The indirect method of measurements was also used in the case of the Vishay Semiconductors VEML6070 that was the one of two UVI sensors that was selected for the use in the flying weather station. The second one was the SI1145, also selected in [7].

Overall, the above comparison of the selection results shows that although both the measurement range (pre-selection criterion) and the IQ dimensions used in the selection criteria do not contraindicate the use of some sensors, the results of our selection are consistent with the mean observed in the literature.

The group of temperature and humidity sensors is very diverse, and there is no sensor that is used the most. In papers [19,21] the Adafruit DHT11 was used, as it was considered very cheap and popular. This sensor does not meet the Criterion 2 of our pre-selection, carried out for use in Krakow, due to the too-high minimum measured temperature (Table 5). However, according to the same Criterion 2 (as a reminder, this is a site-dependent sufficient range of measurements), authors from Khulna (Bangladesh) [19] and Phagwra (Punjab, India) [21], can use this sensor because there is no frost in these locations.

A relatively large group of papers [20,22,24,28] considered another sensor produced by Adafruit, namely the DHT22. The paper [8], in which the SparkFun RHT03 is used, should also be included in this group. The RHT03 is a DHT22 clone with its pros and cons. The criteria that led to the selection of the RHT03 as the most suitable for temperature and humidity measurements in a small UAV were weight, size, range, resolution, and cost [8]. The authors of the paper [24] chose DHT22 because they were very keen on the low cost and availability of parts. In the paper [22], the DHT22 was tested as one of three possible sensors but, ultimately, it was not the best. The DHT22 was also used in [20] for measurements of temperature. In our selection, this sensor was too slow to pass the major criterion, but in the above work it was either not considered or, as in the case of [20], it was negligible. The paper [28] presents another disadvantage of the DHT22, namely it less closely approximates the distribution of a typical mercury thermometer than other tested sensors, including the BMP180. In our selection, because this sensor did not pass the major criterion, it was not checked against the minor criteria, i.e., the accuracy of the measurements.

As mentioned in Section 5.2.2, solutions using the three-in-one sensors typically use them for all three possible measurements. As an example, in the works [2,7,9,22] the Bosch BME280 was used. In [7,9], the BME280 was installed on a UAV as a combined ambient sensor. The BME280 was used in stationary weather station [2] because it is integrated, has low power consumption and small size. The paper [22] compares three sensors (the BME280, DHT22, and BMP180) in terms of the use in stationary weather stations, and the BME280 was indicated as ideal for this application due to its interfaces and the integration of all three measurements. In our selection, the BME280 was rejected as the temperature sensor (it does not meet the minor criteria—Table 10) and passed the selection as the humidity one.

The same rule, mentioned in Section 5.2.2, was used for the Bosch BMP280 and its predecessor, the Bosch BMP180, intended for the atmospheric pressure and temperature measurements. In [23], the BMP280 and the Texas Instruments HDC1080 were used as temperature sensors, and the HDC1080 was the humidity one. Both these sensor passed our selection as temperature sensors only. In [20], both the Bosch BMP180 and the Adafruit DHT22 (which do not pass the major criterion of our selection in temperature) were used as temperature sensors, and the DHT22 was used as the humidity one. The same set of sensors, enriched with the Sensirion SHT21, was used in [28], where the BMP180, the DHT22, and the SHT21 were used as temperature sensors, and the DHT22 and the SHT21 were used as humidity sensors. In our selection, the BMP180 has not been tested, but according to the technical literature, it is to be slightly worse than the BMP280, which took part in the proposed selection.

The SHT10, mentioned above as used in [20], and other products of Sensirion, such as the SHT75 used in [25], and the SHT21 used in [26] had either the EOL status (SHT10, SHT75) or were not recommended for new designs (SHT21). In the case of the SHT10, the results accuracy was satisfactory to the authors [20]. The SHT75 was chosen for its resolution and stability over different atmospheric conditions [25]. The SHT21 was used for the needs of a low-cost system for use on farms with minimal power requirements (so that it can be powered by solar panels) [26]. In this paper, the newer Sensirion products, SHT30 and SHT35, with similar technical parameters to the SHT75 and the SHT21, were a subject of the proposed selection. Both passed the selection as temperature sensors, and the SHT30 also as a humidity sensor.

The sensors selected with the use of a preliminary and less-formalized version of our selection criteria were installed on the target weather station [18], built with the use of the UAV and WebRTC-based universal framework [17]. Results of long-term tests of this flying weather station, which lasted from early June to late November [18] confirm the good accuracy of the selected set of sensors.

6. Proposed Selection in Light of Criteria Known from the Literature

A tabular summary of the criteria for sensor selection known from the literature is presented in Table 1 in the second section. One-third (5 of 14) of summarized cases are analyses based on a literature review [7,21,26–28]. The rest of the criteria listed in Table 1 include the cost of the sensor [8,22–24] (which should be low [22–24]), the range of measurements [8], stability over different atmospheric conditions [25], reliability in high temperatures [9], resolution of the measurement [8,25] (which should be high [25]), weight and size of a sensor [8], and energy efficiency [9].

In the case of the work presented in this paper, two of above selection criteria were adopted explicitly. The literature review was the basis of sensors' pre-selection. The low cost of sensors was the Criterion 1 of sensors' pre-selection. The sufficient range of measurements was the Criterion 2 of sensors pre-selection. Stability over different atmospheric conditions was taken into account during tests for the purpose of checking the fulfillment of both the major criterion (change of temperature in air conditioning laboratory room) and the minor criteria (field tests in different weather conditions).

Moreover, some of the selection criteria listed in Table 1 have been met implicitly, as a side effect of meeting some assumption or criterion, or as a direct result of the selection made. Such a criterion is reliability in high temperatures, formulated in this paper [9]. Although the microclimate of Krakow means that the reliability of measurements in high temperatures do not have to be taken into account, all sensors that passed pre-selection are able to operate in temperatures at least up to +85 °C (Table 5). The HTU21D, which was selected as the temperature and humidity sensor, is able to work at temperatures of up to +125 °C. For comparison, the S-THB-M008 sensor, selected in [9] in terms of reliability in high temperatures, is able to carry out measurements from −40 to +75 °C. The other sensor selected in [9] in terms of reliability in high temperatures, namely the BME280, passed the proposed selection as the atmospheric pressure sensor.

A side effect of meeting the minor criteria is the high resolution of the measurement, used as a selection criterion in these papers [8,25]. Although the accuracy, not the resolution, is checked with the minor criteria, both these quantities must be large enough to assure good and satisfactory quality of measured information. As a result, the selected sensors have a relatively high resolution, expressed both in bits per sample and in units of measured quantity (Table 13). As an example, the HTU21D, selected as the temperature and humidity sensor, used 12 bits per sample, which results in resolutions of 0.04 °C (temperature), and 0.04% (humidity). The BME280, which also passed the selection as the humidity sensor, has resolution for the humidity measurements of 16 bits and 0.008%.

Table 13. Resolution of sensors selected for the use in the flying weather station.

Sensor Type	Resolution	Bits per Sample
HTU21D	0.04 °C, 0.04%	12 bit
BME280	0.18 Pa, 0.01 °C, 0.008%	20 bit [1], 16 bit [2]
SI1145	N.A.	16 bit
VEML6070	N.A.	16 bit

[1] pressure, [2] temperature and humidity.

For comparison, the specification of the SHT75, selected in the paper [25] in terms of its high resolution, shows 12 or 14 bits per sample in temperature, which gives resolutions of 0.04 °C or 0.01 °C respectively. The same sensor has a resolution of 12 bits and 0.05% in humidity measurements. The RHT03, selected in [8], has 16 bits per sample, 0.1 °C of resolution in temperature and 0.1% in humidity. This shows that the proposed selection turned out to be more restrictive in terms of high measurement resolution than the selections that explicitly used this criterion.

The size of the IoT carrier used in the UAV and WebRTC-based framework serving as a target system and its large load capacity mean that the weight and size of the sensors do not have to be taken into consideration during the selection. Nevertheless, the assumption of low cost combined with the minor and major criteria results in the modern sensors being preferred, which is also reflected in their light weight and small size. As is shown in Table 14, the weight of the selected weather sensors (including their boards) was from 0.5 g (VEML6070) to 1.8 g (HTU21D) nominally, and it was confirmed by measurement (with accuracy to balance resolution). The length of selected sensors was from 13 mm (HTU21D) to 20 mm (SI1145), and the width from 10 mm (BME280) to 18 mm (SI1145). For comparison, the RHT03 sensor, which in the paper [8] was selected in terms of weight and size, is both heavier (4 g) and larger (37 mm × 21 mm) than any of the sensors selected for the use in the flying weather station.

Table 14. Weight and size of sensors selected for the use in the flying weather station.

Sensor Type	Weight		Size
	Measured	Nominal	
HTU21D	2 g	1.8 g	13 mm × 15 mm
BME280	2 g	1.7 g	15 mm × 10 mm
SI1145	2 g	1.4 g	20 mm × 18 mm
VEML6070	1 g	0.5 g	14 mm × 13 mm

The last but no less important criterion for selecting a sensor, summarized in Table 1, is energy efficiency. The BME280 air pressure, temperature, and humidity sensor was reported in the paper [9] as having enough energy efficiency to be selected for use in a UAV-based weather station. The same sensor was chosen in this paper as the atmospheric pressure sensor for the flying weather station. Current energy consumption of this sensor, measured during its work on the UAV and WebRTC-based platform, was 340 µA. The current consumption of the weather sensors working on the flying weather station, shown in Table 15, ranged from 110 µA (VEML6070) to 420 µA (HTU21D).

Table 15. Energy consumption of sensors selected for the use in the flying weather station.

Sensor Type	Power	Suply Current
HTU21D	1.4 mW	420 µA
BME280	1.2 mW	340 µA
SI1145	0.8 mW	250 µA
VEML6070	0.4 mW	110 µA

The low energy consumption of the selected sensors during their operation in the flying weather station was achieved by choosing fast response sensors (due to the major criterion). This results in a very short active measurement period and a long inactive standby period. For comparison, the measured current consumption of the Aosong DHT22 temperature and humidity sensor, which was not able to meet the major criterion, was 2.5 mA in the same circumstances. However, if the selected sensors do not provide low idle power consumption, the effect of better energy efficiency will not occur.

7. Use Cases

This selection process is designed for building custom mobile weather stations or a small series of specialized mobile weather stations that use low-cost sensors. However, the proposed method is more versatile and allows for more applications than just cheap weather stations. In these applications, the full selection algorithm (presented in Figures 1 and 2) can be used, or only some of its elements, e.g., only the actual selection (skipping the pre-selection).

Special cases of using the proposed selection method may be the assessment of the quality of data obtained from crowdsourcing or a situation when all available sensors will be used for measurement and the data will be selected post-hoc. In both of these cases it can be assumed that for each sensor used, the answer to the question "is the sensor able to perform the desired measurement?" is "yes, it is". It has been tested experimentally during the system operation. Therefore, it is enough to use only minor criteria for selection (skipping both the pre-selection and whether the major criterion is met).

It is also possible that the major criterion and the minor criteria are contradictory. This means that increasing accuracy significantly increases response time—so much so that response time begins to exceed the time constraints imposed by the system operating conditions. Two solutions are then possible. First, the minor criteria may be changed to be less restrictive. As an example, the measures of the LoA and the LoS will be defined in a less stringent manner than described in Section 3.4. Second, the technical assumptions of the system operation will be changed to be less restrictive so that the duration of the polling cycle will be increased over the sensor's response time. This will entail a reduction in the system functionality. If neither of these solutions is possible, the sensor must be excluded.

The selection process should be performed at least once, i.e., at the system integration stage. Nevertheless, it may happen that during the operation of the system it will be necessary to select the sensors again. In particular, such a need may arise in the event of one of the following events:

- a significant change in the location of the system (e.g., the system will be moved from valley to mountains or from mountain area to seaside);
- the task has been changed to a more restrictive one, e.g., one requiring greater accuracy;
- the requirements of the data recipients have changed, for example, they now demand e.g., greater accuracy or greater spatial resolution;
- a different reference station was used, or the current reference station was renovated, resulting in the replacement of the station's sensors or their recalibration;

- the response time requirements have been changed to more restrictive or less restrictive—e.g., when lowering the requirements, it may turn out that excluded sensors can be used due to their important features; and
- during the operation of the mobile weather station, it turned out that its measurement system was less stable in various weather conditions than it was when checked during the selection process.

The proposed selection process can take a long time. This is not a problem at the stage of building the system, because the selection of sensors can be combined with functional tests of the system. However, the need for re-selection may result in the need to automate the entire selection process. The limitation, however, is the necessity to repeat experiments, especially those made for the needs of minor criteria.

8. Limitations and Future Work

The proposed method is limited to sensors whose electrical response time is equal to (or close to) the actual response time. It cannot be used for the selection of sensors that are characterized by large actual response times and small electrical ones (e.g., the MQ-135 gas sensor used in our pollution-monitoring system [35]), because the different approach for response time affects both the major criterion (response time used in this criterion defaults to electrical) and the minor criteria (in such sensors, the large amount of measured data is inherently untrustworthy). This problem is similar to the problem of conflict between the major criterion and the minor criteria, described in the previous section. However, because there is a contradiction between the actual response time (not the electrical one) and the accuracy of the measurement, a satisfactory compromise can be found (e.g., using quasi-stationary measurements at established measurement points). The IQ-oriented selection process of such a class of sensors remains for future considerations, along with the analysis of applicability of the two minor criteria for the selection of mobile devices for the purposes of weather crowdsourcing.

9. Conclusions

One of the most important types of data systems required by smart city management systems are weather-related data systems. Due to the specificity of the urban environment, the density of the deployment of weather measuring points should be high, or even very high, which requires a large number of relatively cheap weather data sources. This requirement naturally leads to the need for the use of low-cost sensors.

However, the use of low-cost weather sensors for professional purposes is a big challenge, because of the well-known problem of their inaccuracy and the uncertainty of the results of weather measurements. In this paper, we propose to solve this problem (or at least reduce it) with the use of the two-stage selection of sensors, consisting of a pre-selection carried out on the basis of the literature and the actual selection based on experiments. The proposed solution can either alter or extend existing solutions, such as sensor calibration supplementing the factory one. What distinguishes our solution from similar selection methods is the use of the sensors's response time as the major criterion and the use of two minor criteria related to the intrinsic information quality of the measurement information. The latter required us to introduce definitions of the LoA and the LoS. The LoA reflects the difference between the sensor measurements and the reference weather station measurements, and the LoS determines whether the information is satisfactorily believable.

Our method of selection was tested by using twelve weather sensors (eight of them measured temperature and humidity, two measured temperature, humidity, and air pressure, and two measured UV index) from different manufacturers. Results show that the proposed two-stage sensor selection not only allows one to achieve the accuracy of weather parameters when comparing with weather data obtained from the reference weather station, but also allows us to meet other selection conditions presented in the literature, such as weight and size of a sensor, energy efficiency, and so on.

Although the proposed solution was intended for sensors measuring weather factors, the method itself is more versatile and allows for more uses of this selection solution than just low-cost weather stations.

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Abbreviations

The following abbreviations are used in this manuscript:

BLoS	Binary Level of Satisfaction
DQ	Data Quality
EOL	End of Life
HTML5	Hypertext Markup Language version 5
IQ	Information Quality
IoT	Internet of Things
LoA	Level of Accuracy
LoS	Level of Satisfaction
OS	operating system
SBC	Single-Board Computer
SPA	Single Page Application
UAV	Unmanned Aerial Vehicle
UV	Ultraviolet
UV-A	Ultraviolet A
WebRTC	Web Real-Time Communications
WHO	World Health Organization
WoT	Web of Things

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